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Analysis of Risks of Interbasin Biota Transfers Potentially Linked to System Failures in the Northwest Area Water Supply Project

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Risks of Biota Transfers Potentially Associated with Surface Water Diversions Between the Missouri River and Hudson Bay Watersheds

Analysis of Risks of Interbasin Biota Transfers Potentially Linked to System Failures in the Northwest Area Water Supply Project

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Executive Summary

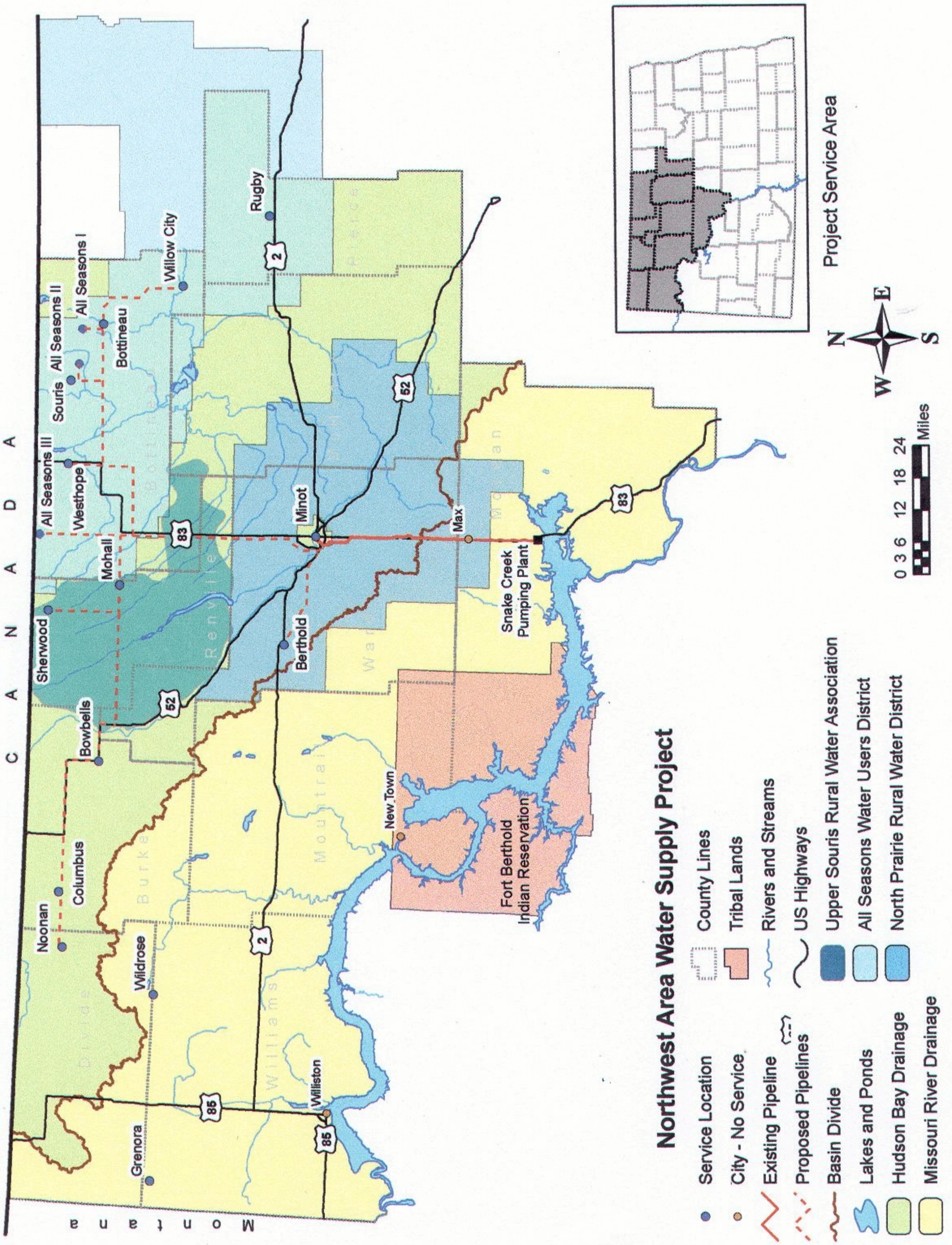
Through the Garrison Diversion Unit Reformulation Act of 1986, the Municipal, Rural and Industrial Water Supply (MR&I) program was authorized by the US Congress on May 12, 1986. This act authorized the appropriation of $200 million of Federal funds for the planning and construction of water supply facilities throughout North Dakota. The Northwest Area Water Supply (NAWS) project was developed as a result of this authorization and was initiated in November 1987. NAWS is a bulk water distribution system that will service local communities and rural water systems in 10 counties in northwestern North Dakota, including the community of Minot (Executive Summary, Figure 1). Source waters for NAWS will be derived from Lake Sakakawea in the Missouri River basin of North Dakota and will be transferred to Minot, North Dakota, in the Souris River basin of the Hudson Bay watershed. Hence, an interbasin water diversion will result from the water supply project.

The Dakotas Area Office (DKAO), Bureau of Reclamation (Reclamation) requested technical support from the US Geological Survey (USGS) Columbia Environmental Research Center (CERC) for an evaluation of the risks of biota transfers potentially associated with the water transfer between the Missouri River basin in North Dakota and the Hudson Bay basin in North Dakota. This analysis considered (1) an evaluation of failures in control systems (particularly water treatment and containment) and (2) a preliminary analysis of risks and consequences potentially linked to biota transfers potentially realized, if control system[1] failure occurred.

The analysis of risks detailed in this report follows the process and employs the tools of risk analysis previously applied in other USGS studies completed for Reclamation. The NAWS investigation focused on existing data and available information to address the interrelationships between biota transfers and control system failure, and was implemented through a comprehensive literature survey targeted on biota of concern and the engineering alternatives being considered in the biota treatment alternatives being considered in conceptual designs for NAWS infrastructure. A variety of methods were applied to risk and failure analysis, with a particular focus on risk reduction measures potentially of value to Reclamation in their risk management activities. Earlier studies completed by USGS had also considered issues linked to proposed interbasin water diversions between the Missouri River and Red River basins in North Dakota, and shared a common concern of coincidental species invasions or shifts in metapopulations potentially resulting from managed diversion of waters between these river basins. In the present investigation the analysis builds from earlier findings and focuses on species identified as most likely of concern to the analysis process. Here, output from the analysis of risks is subsequently characterized with respect to the biota transfer risks associated with these high-priority species. Risk reduction associated with proposed engineering infrastructure for NAWS, especially water treatment technologies targeted on species of concern,

[1]Control system refers to engineering infrastructure encompassing treatment, containment, and conveyance as captured by each alternative considered in conceptual water system designs.

Executive Summary, Figure 1. Service area captured by the Northwest Area Water Supply project (NAWS).



Northwest Area Water Supply Project
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Existing Pipeline
Proposed Pipelines
Basin Divide
Lakes and Ponds
Hudson Bay Drainage
Missouri River Drainage
County Lines
Tribal Lands
Rivers and Streams
US Highways
Upper Souris Rural Water Association
All Seasons Water Users District
North Prairie Rural Water District
C A N A D A
Montana
Noonan
Columbus
Bowbells
Sherwood
Mohall
All Seasons III
Westhope
Souris
All Seasons II
All Seasons I
Bottineau
Willow City
Rugby
Minot
Berthold
Max
New Town
Wildrose
Grenora
Williston
Snake Creek Pumping Plant
Fort Berthold Indian Reservation
85
2
52
83
0 3 6 12 18 24 Miles
N
E
S
W
Project Service Area

have been considered as risk management tools intended to address uncertainties linked to engineering failures and stochastic processes characteristic of the biota transfer process.

Reclamation is currently preparing their Draft Environmental Impact Statement for the NAWS project, and those control systems being considered as alternatives therein were considered in this analysis of risks linked to biota transfers. An existing pipeline connecting source waters from Lake Sakakawea will serve the NAWS service area, relying on one of four proposed treatment regimens to offset risks poised by the proposed interbasin water diversion. These alternatives are summarized in Executive Summary, Table 1. In brief, these alternatives included a range of water treatment technologies that presented a spectrum of risk reduction potential.

Executive Summary, Table 1. Summary of conceptual designs of water treatment operations that are being considered for interbasin water diversion potentially achieved as part of NAWS project.

Alternative	Step 1	Step 2	Step 3	Step 4	Continental Divide	Step 5
A	Chlorination-Chloramination					Minot WTP
B	Coagulation-Flocculation-Sedimentation	UV Treatment	Chlorination-Chloramination			Minot WTP
C	Dissolved Air Flotation	Media Filtration	UV Treatment	Chlorination-Chloramination		Minot WTP
D	Pre-treatment	Microfiltration	UV Treatment	Chlorination-Chloramination		Minot WTP

Alternative A: Chemical Treatment. The Chemical Treatment alternative or the “no action alternative” was originally proposed in the *Environmental Assessment* (Houston Engineering et al. 2001) and *Finding of No Significant Impact* (Reclamation 2001) for the NAWS project. This alternative is not intended to meet requirements under the Safe Drinking Water Act (SDWA) until source waters have been treated in Minot. The alternative was designed to provide biota control through disinfection at the source using combined chlorine-chloramine pre-treatments, where a chloramine residual would be maintained in the pipe for control of biofilm. The pre-treatment facility would provide 3-log inactivation of *Giardia* and 4-log inactivation of viruses prior to crossing the watershed boundary (see Houston Engineering et al. 1995a,b). The North

Dakota Department of Health agreed that the pre-treatment facility would achieve the primary disinfection credit required and no primary disinfectant would be required at the water treatment plant (WTP) in Minot (see Reclamation 2007).

Several mechanical and structural features and operational procedures will be built into this alternative (see Houston Engineering 1998, 2001). The final step in this proposed alternative includes final treatment to SDWA standards at an upgraded facility in Minot, currently envisioned as a process including conventional lime softening with ultraviolet (UV) irradiation proposed for disinfection (Reclamation 2007, 2001). Lime softening can provide good microbial treatment through a combination of inactivation by high pH and removal by sedimentation in addition to its role to treat source waters for water hardness (Letterman 1999).

Alternative B: Basic Treatment. Alternative B includes a conventional coagulation-flocculation-sedimentation process in series with UV irradiation, chlorine disinfection, and chloramine residual at the source. The final treatment process would occur at the Minot WTP. As proposed, this process would consist of a pumped flash-mix[2] facility and a partially buried concrete basin for coagulation, flocculation, and sedimentation. Source waters would then be UV disinfected and chloramines added to provide residuals before being transferred from the Missouri River basin (HUC10) into the Souris River subbasin (HUC0901) of the Red River basin of North Dakota (HUC09).

Alternative C: Dissolved air flotation (DAF) and media filtration. Alternative C included a Dissolved Air Flotation (DAF) pre-treatment followed by a media filter, UV disinfection, and chlorine treatment and chloramine addition to maintain chlorine residual in the treated waters. This alternative would provide water in compliance with SDWA immediately upon leaving the treatment facility, then conventional lime softening would occur at the Minot WTP.

Alternative D: Microfiltration. To provide a full range of alternatives for biota treatment, a membrane filtration alternative—microfiltration—has also been included for this analysis. Microfiltration provides a practically absolute barrier to particles passing through the control system. From a regulatory perspective, microfiltration is granted substantial log removal credit for *Giardia* and *Cryptosporidium*, depending on membrane of choice and its application within a control system. Membrane alternatives would include a pre-treatment step dependent on the type and size of membrane technology specified in the control system's final design. Once biota treatment was completed at the source, this alternative could provide SDWA quality water immediately upon leaving the treatment facility.

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[2]The mixing of coagulant chemical and source waters is commonly referred to as flash mixing, with the primary purpose of the flash-mix process being to rapidly mix and equally distribute the coagulant chemical throughout source water. The reaction between the colloidal matter with the coagulating chemical occurs within seconds, resulting in formation of very small floc particles. As the floc clumps together, larger, heavier floc is formed which can settle out or be removed by filtration.

Given these alternatives and earlier findings summarized by USGS for related biota transfer issues focused on the Red River Water Supply (RRVWS) Project (USGS 2006, 2005a,b), high-priority biota of concern for the NAWS project included various disease agents (both fish diseases and zoonotic diseases) and cyanobacteria listed in Executive Summary, Table 2.

Executive Summary, Table 2. For the NAWS project, representative species that shaped the analysis of risks related to biota transfers linked to interbasin water diversions included the high ranking candidate species identified as biota of concern for the analysis of risks for the RRVWS project (see USGS 2005a).
Microorganisms and Infectious Diseases
Enteric redmouth Infectious hemtopoietic necrosis virus (IHNV) *Escherichia coli* (various serotypes)* *Legionella* spp.* *Salmonella* spp. (including, but not limited, to *S. typhi*, *S. typhmurium*, other *Salmonella* serotypes, and other water-borne infectious diseases)*
Protozoa and Myxozoa
Myxosoma cerebralis (*Myxobolus cerebralis*) *Polypodium hydriforme* *Cryptosporidium parvum** *Giardia lamblia**
Cyanobacteria
*Anabaena flos-aquae** *Microcystis aeruginosa** *Aphanizomenon flos-aquae**
Biota associated with biosolids and sludge associated with interbasin water transfers, including: ● Potential transfer of plant and disease organisms (plant, wildlife, and human) ● Potential biota transfers derived from sludge and biosolid disposal
*Species distribution is cosmopolitan throughout North America, but species included as part of the analysis, given the relative importance of shifts in metapopulations that might be linked to, e.g., disease outbreaks.

For the NAWS project, the analysis of risks linked to control system failure conditioned the risks linked to biota transfers. From a risk management perspective, managing risks associated with control system failure potentially minimized risks and consequences of biota transfers potentially associated with interbasin water diversions between Missouri River and Hudson Bay basins (for NAWS, the Souris River subbasin within the Hudson Bay watershed). As such, an analysis of risks associated with failure of controls systems—water treatment and conveyance—reflects a preliminary evaluation of system reliability, given the critical function that the control system plays in assuring that biota transfers are not realized in the process of water diversion. System failure could result in biota transfer and potentially the establishment of invasive species or shifts in metapopulations of, e.g., disease agents cosmopolitan in their distribution across the northern Great Plains and Great Lakes basin.

Conveyance risk is common across all the alternatives currently identified in the NAWS DEIS, but treatment alternatives provided ranges of risk reduction potential as indicated in Executive Summary, Table 3.

Executive Summary, Table 3. Summary of initial evaluation of risk reduction credits earned by each of the four alternatives being considered in the DEIS.

Alternative	Step 1	Step 2	Step 3	Step 4	Within-basin		Step 5*	Total Rank Score
A	Chlorination-Chloramination					Continental Divide	Minot WTP	
Rank	1				1		2	3
B	Coagulation-Flocculation-Sedimentation	UV	Chlorination-Chloramination				Minot WTP	
Rank	1	1	1		3		1	4
C	Dissolved Air Flotation	Media Filtration**	UV	Chlorination-Chloramination			Minot WTP	
Rank	1	1	1	1	4		1	5
D	Pre-treatment***	Microfiltation	UV	Chlorination-Chloramination			Minot WTP	
Rank	1	2	1	1	5		1	6

*Minot WTP will be upgrade under various alternatives; 1=current operation continues, 2=upgraded beyond current operating specifications.

**Depending on media of choice, risk reduction score may be increased.

***If pre-treatment consists of coagulation-flocculation-sedimentation, rank score as indicated. If otherwise, rank score adjusted accordingly.

Risk reduction credits were assigned to each compartment within the proposed treatment operations. Rank scores reflected assigned values for ordinal data, with assigned values being simple binary scores or categorical rank-scores weighted so increasing value captured greater reduction in risks, e.g., 0 was assigned to alternatives lacking water treatment in the source area basin and 1 was assigned to alternatives having proposed water treatment near source area in the Missouri River basin.

Following the assignment of risk reduction credits to each compartment within each of the alternatives, component scores were summed to yield total risk reduction credits. On the basis of this categorical analysis, the current menu of alternatives yielded a range of risk reduction credits achieved within-basin for each system—in ascending order, Alternative A < Alternative B < Alternative C < Alternative D. When considered from source to terminus, risk reduction outcomes were anticipated for treatment at Minot WTP and yielded total risk reduction credits in ascending order are Alternative A < Alternative B < Alternative C < Alternative D. Risks associated with water transmission pipelines are common to each of the alternatives; hence, water transmission risks are not discriminating among alternatives in this analysis. As noted in USGS (2006), when operating practices related to treatment regimens are incorporated into final designs, differences in alternatives may be realized and treatment-conveyance interactions should be evaluated as part of future engineering analyses, e.g., operation of water treatment systems may yield different inputs to water conveyance which confer discriminating risks within the control system's full design.

In the current analysis, a number of uncertainties and assumptions regarding each alternative and risks associated with these alternatives must be incorporated into interpretative context for refining subsequent iterations of risk reduction analysis. While the current analysis of risks acknowledges differences among alternatives, the summary findings reflect assumptions of risks being identical across systems, e.g., risks of pipe breaks as measured by "breaks per pipe-mile per year" are assumed identical under potentially different operating conditions for treatment processes incorporated into final designs. Future engineering risk analysis may refine this assumption to capture differences across locations and component parts of the transmission system, e.g., control valves, pipe configurations.

The outcomes of risk analysis are intended to help Reclamation develop informed resource management decisions which will directly serve the NAWS service area and help develop risk-based water resource management plans. The uncertainty analysis completed in parallel with the characterization of risks identified data gaps in the existing literature. Available data gaps were identified that will be addressed through Reclamation's adaptive management plan, and may translate into research needs potentially of value to USGS.

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Analysis of Risks of Interbasin Biota Transfers Potentially Linked to System Failures in the Northwest Area Water Supply Project

1.0 Introduction

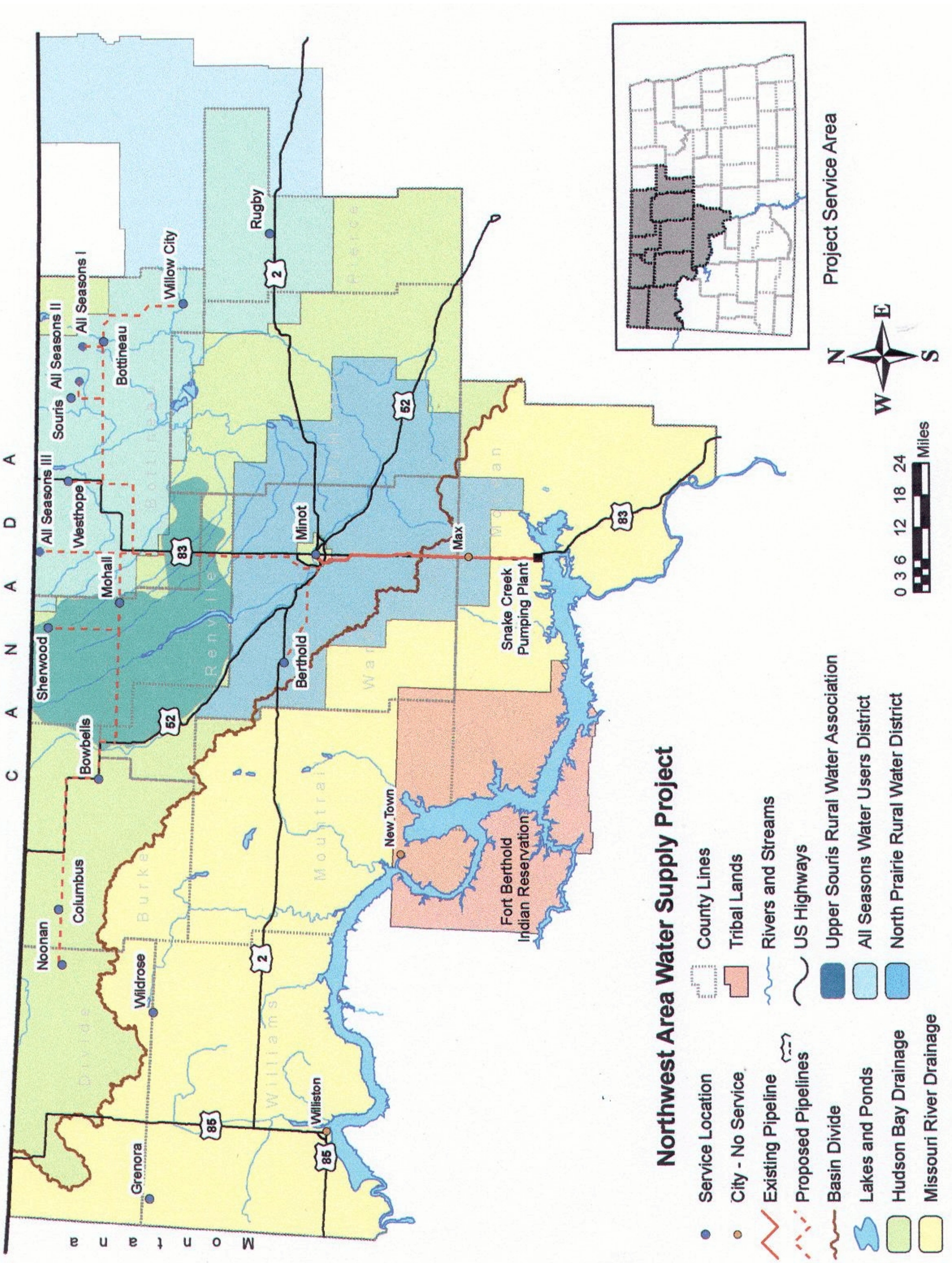
Through the Garrison Diversion Unit Reformulation Act of 1986, the Municipal, Rural and Industrial Water Supply (MR&I) program was authorized by the US Congress on May 12, 1986. This act authorized the appropriation of $200 million of Federal funds for the planning and construction of water supply facilities throughout North Dakota. The Northwest Area Water Supply (NAWS) project was developed as a result of this authorization and was initiated in November 1987.

NAWS is a bulk water distribution system that will service local communities and rural water systems in 10 counties in northwestern North Dakota, including the community of Minot. Source waters for NAWS derived from Lake Sakakawea in the Missouri River basin of North Dakota will be transferred to Minot, North Dakota in the Souris River basin of the Hudson Bay watershed. Hence, an interbasin water diversion will result from the water supply project. Reclamation completed an *Environmental Assessment* (Houston Engineering et al. 2001) and *Finding of No Significant Impact* (FONSI; Reclamation 2001), and construction on the project was begun in April 2002. However, in October, 2002 the Province of Manitoba filed a legal challenge in US District Court in Washington, DC to compel the Department of the Interior to complete an EIS on the project. A Court Order dated February 3, 2005, remanded the EA to Reclamation for completion of additional environmental analysis that considers an integrated analysis of the possibility of leakage and the potential consequences of the failure to fully treat the Missouri River water at its source, given the agency's awareness of treatment-resistant biota. On March 6, 2006, Reclamation published a Notice of Intent (NOI) to prepare an environmental impact statement in the *Federal Register* (Volume 71, Number 43).

While the litigation filed by Manitoba was pending, Court-approved construction continued on the water transmission component of the project from Lake Sakakawea to Minot. Construction of the transmission pipeline that would convey Missouri River water to Minot for NAWS Project began in April 2002, and the 45-miles pipeline is targeted for completion in 2007. Work on the distribution system and other features of the project is proceeding as the District Court grants approval.

The Dakotas Area Office (DKAO), Bureau of Reclamation (Reclamation) requested technical support from the US Geological Survey (USGS) Columbia Environmental Research Center (CERC) for an evaluation of the risks of biota transfers potentially associated with the water transfer between the Missouri River basin in North Dakota and Hudson Bay basin in North Dakota (Figure 1). Reclamation requested:

Figure 1. Service area captured by the Northwest Area Water Supply project (NAWS).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N
E
S
W
0 3 6 12 18 24 Miles
C A N A D A
Montana
Noonan
Columbus
Bowbells
Sherwood
Mohall
All Seasons III
Westhope
Souris
All Seasons II
All Seasons I
Bottineau
Willow City
Rugby
Minot
Berthold
Max
Snake Creek Pumping Plant
New Town
Fort Berthold Indian Reservation
Wildrose
Grenora
Williston
2
52
83
85

- an evaluation of failures in control systems[3] (particularly water treatment and containment) to be addressed in the Draft Environmental Impact Statement (DEIS) being prepared by Reclamation as part of their National Environmental Policy Act (NEPA) compliance process, and
- a preliminary analysis of risks of effects and consequences for NAWS service areas associated with biota transfers potentially linked to control system failure.

This report summarizes the technical findings of the risk analysis, including an overview of the analysis, assessment, and management process. The analysis of risks detailed in this report follows the process and employs the tools of risk analysis applied in earlier studies completed by USGS (2006, 2005a,b) that focused on similar issues for the Red River Valley Water Supply (RRVWS) project. As such, these earlier studies considered issues linked to proposed interbasin water diversions between the Missouri River and Hudson Bay basins and shared a common concern for coincidental species invasions or shifts in metapopulations potentially resulting from managed diversion of waters between these river basins. In the present investigation the analysis builds from the findings in USGS (2006, 2005a,b) and focuses on species identified as most likely of concern to the analysis process. Here, output from the analysis of risks is subsequently characterized with respect to the biota-transfer risks associated with these high-priority species. Additionally, following USGS (2005b, 2006), risk reduction associated with proposed engineering infrastructure for NAWS—especially water treatment technologies targeted on species of concern—have been considered as risk management tools intended to address uncertainties linked to engineering failures and stochastic processes characteristic of the biota transfer process.

This report consists of six sections, including this Section 1 that provides an overview of the origins of this technical support project. Section 2 provides a summary of the risk analysis, risk assessment, and risk management process, particularly as those activities were implemented, following available guidance for this technical effort. The section closes with outcomes of Problem Formulation and development of conceptual models that guided the risk analysis. The risk analysis is the primary focus of Section 3, which also outlines the tools applied to the analysis. Section 4 summarizes the characterization of risks and biological consequences, which is consistent with the process followed in previous reports (USGS 2005a,b, 2006). An initial evaluation of system failures and uncertainties intended to inform decision makers and help develop risk management plans as the NAWS project develops is also considered in Section 4. A summary of technical findings intended to inform risk management activities and compiled references cited throughout the text follow in Section 5 and Section 6, respectively. Three appendices have also been included as separate technical summaries of materials and concepts critical to the technical analysis of risks.

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[3]Control system refers to engineering infrastructure encompassing treatment, containment, and conveyance as captured by each alternative considered in conceptual water system designs.

2.0 Overview of the Process for Analyzing and Informing Risk Management Decisions

The commonly implemented process of evaluating risks, particularly within the context of environmental issues and a multiple stressor approach to cumulative risk assessment, is highly interactive (Figure 2; see EPA 2003; Ferenc and Foran 2000; Foran and Ferenc 1999). For this report, the technical activity focused on biota transfers potentially linked to NAWS water resource management practices, particularly as those transfers that may result from system failures associated with engineering infrastructure envisioned in the Draft Environmental Impact Statement (DEIS) currently being prepared by DKAO (*Federal Register*, Volume 71, Number 43). While the context of this risk analysis resolves on both human and nonhuman receptors as targets of biological agents potentially entering the Souris River basin as a consequence of water diversion from the Missouri River, the focus of the current analysis ranges across various levels of biological organization and spatial scales; hence, much of the process and language used in completing the work reflects an ecological context for evaluating and characterizing risks. As with other reports prepared by USGS/CERC to help inform water resource management decisions, the integrated analysis of risks summarized in this report was not intended to be an ecological risk assessment nor a human health risk assessment. Rather, the analysis focused on risks and biological consequences of biota transfers potentially associated with water diversions from the Missouri River or competing pathways for such biological incursions.

Figure 2 summarizes the process we followed in completing this analysis. USGS/CERC identified biota transfer issues that appeared as "drivers" for the technical support request issued from Reclamation. Planning and scoping discussions with Reclamation regarding biota transfer issues were reinforced through background information regarding the historical, technical, and legal foundations of NAWS (see, e.g., http://design.eng.umanitoba.ca/resources/garrison_full.html last accessed May 30, 2007, http://www.gov.mb.ca/waterstewardship/transboundary/positions/man-position/backgr.html last accessed May 30, 2007, Reclamation 2006c, US District Court for District of Columbia 2005a,b, Reclamation 2001a,b). Biota transfer issues of NAWS are technically similar to those biota transfer issues previously considered by USGS for the RRVWS project (USGS 2005a,b, 2006); hence, biota of concern and pathways linking source (Missouri River waters) and receiving systems in the service area in Souris River basin (Figure 1) were identified based on selection criteria previously characterized (USGS 2005a). These species and pathways were then incorporated into conceptual models developed for NAWS, as one of the primary outcomes of Problem Formulation. The process summarized in Figure 2 is briefly characterized and outcomes from Problem Formulation that provided the foundation for the analysis and characterization of risks are summarized to close the section of this report.

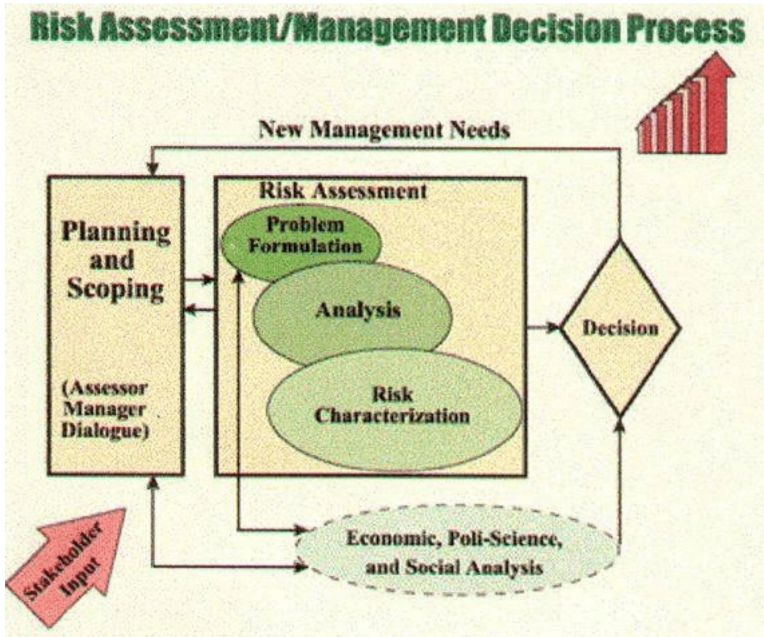


Figure 2. Risk assessment and management process adopted for the NAWS biota transfer evaluation (see USGS 2005a for detail; see also EPA 2003).

2.1 Framework for Evaluating Risks of Biota Transfer for NAWS

Risk analysis and the subsequent process of assessing risks and consequences of targeted events has a wide range of applications to evaluations of:

- ecological condition,
- accidental events,
- financial concerns, and
- technology issues.

Each of these applications is relevant to the issues that Reclamation faces in its management of water resources across the western US.

In its simplest summary, the analysis, assessment, and management of risks is captured by a stepwise, iterative process wherein (1) questions are formulated, (2) observations or "experiments" are conducted wherein answers are developed to address those questions, and (3) decisions are made given the answers to the questions that initiated the process (see USGS 2005a, EPA 1992, EPA 1998, EPA 2003, NRC 1983, NRC 1994). Management decisions that result from the initial assessment may (1) yield sufficient management-critical support for a particular management action, or (2) the analysis process may be reiterated to address critical data gaps identified as outcomes of the initial "query-answer routine." For example, answers developed during the first iteration may not be sufficient to support management decisions when the level of uncertainty exceeds the risk-tolerance of the decision-makers. Additionally, if sufficient evidence in support of a management decision is derived following completion of the process, parallel technical support efforts may be conducted as part of an adaptive management program that develops a monitoring program that parallels an on-going management activity (Stahl, et al. 2001).

CERC conducted the technical analysis of risks and consequences associated with biota transfers potentially associated with interbasin water transfers following available guidance (EPA 1992, EPA 1998, EPA 2003 NRC 1983, NRC 1994), including that developed for hazard assessment and critical control point (HACCP) analysis for aquatic nuisance species and similar applications (e.g., see Minnesota Sea Grant/Michigan Sea Grant 2001, ASTM 2007).

2.2 Problem Formulation and Development of Conceptual Models

Consistent with the risk assessment process practiced for issues related to environmental and technological interactions, conceptual models or nested conceptual models were developed to characterize the issues related to biota transfers associated with interbasin water diversions. As part of Problem Formulation, preliminary models were developed wherein (1) biota of concern were identified and characterized with respect to their biological and ecological attributes that may promote their transfer and establishment in previously unoccupied areas (e.g., life-history attributes likely to influence invasiveness); (2) pathways that potentially link biota of the Missouri River basin (source area) with the Souris River basin (receiving area) were characterized, acknowledging life-history attributes of biota of concern that might enhance the likelihood for invasion and establishment; and (3) ecological receptors likely to be adversely impacted by invasive species were identified. These initial "query-response" couplets relied on previous USGS reports (USGS 2005a,b, 2006) that were focused on similar interbasin water diversion issues for the Red River Valley of North Dakota. Biota of concern considered in this analysis were based on a wide range of species originally identified by Reclamation and stakeholders actively engaged in the water resources issues reflected in the RRVWS project. As in RRVWS project, the technical analysis captured in the NAWS project was shaped in part by concerns related to biota transfers potentially linked to interbasin water diversions; hence, the shared concerns captured a common set of biota of concern. Those representative species most likely to be problematic for biota transfer in RRVWS project were the primary focus in this analysis for NAWS (see USGS 2005a). Similarly, pathways linking these high-priority species to the Souris River basin were considered under the auspices of this technical analysis of biota-transfer risks for NAWS. Within the risk analysis process, and in particular during Problem Formulation, discussions with risk managers provided background for technical support activities for NAWS, as it had for the RRVWS technical activities.

Within an ecological context, assessment endpoints are selected for risk assessment during Problem Formulation. In this current investigation, assessment endpoints were globally identified as valued ecosystem components to be protected, in this instance, populations of ecological receptors and habitats potentially adversely impacted by species invasions consequent to biota transfers linked to water diversions between basins. While a range of professional opinion is evident in the identification and characterization of assessment endpoints and valued ecosystem components, the identification of global assessment endpoints reflects a systems-level focus shaped in part by stakeholder input in the RRVWS experience that guided development of the conceptual model for the NAWS project (Table 1).

Table 1. Global assessment endpoints linking species-specific analysis on selected biota of concern with habitat equivalency analysis supporting analysis of potential economic consequences associated with interbasin water transfers.

Population	Community	Ecosystem
• Extinction • Abundance • Yield or production • Changed age or size-class (demographic structure) • Disease occurrence (changes in mortality or morbidity) • Market or sport value	• Recreational quality • Habitat alteration to less useful or desired type • Changed community structure	• Productive capacity

These global assessment endpoints reflected concerns conveyed by Reclamation and stakeholders, particularly as those regional concerns were captured by the biota of concern identified in USGS (2005a). Although the technical analysis focused on species-level estimators of risk, these species were considered representatives of the much larger body of candidate species potentially of concern for biota transfer (including species invasions). These high-priority species identified in USGS (2005a) then served as portals through which assessment endpoints may be viewed, and the potential adverse affects at the community and ecosystem levels of organization, and population-level effects could be considered. Ecological relevance was an important consideration in selecting representative species of concern and ecological receptors. From an ecological perspective, relevant conditions considered in the process of identifying global assessment endpoints included:

- effects associated with the absence of a species normally expected to occur,
- effects associated with reduction in population size,
- effects associated with altered in community structure,
- habitat degradation or loss, and
- diminished or reduced ecological function.

2.2.1 Measures of Adverse Effects. Measurements of adverse effects, traditionally identified as measurement endpoints (see Suter 1993; EPA 2003, 1998, 1992), were used to quantify adverse effects associated with potentially completed pathways, particularly as those events influenced the evaluation of alternatives and characterization of risks that may occur subsequent to a biota transfer. The primary measures of adverse effects were captured by the biota of concern that guided the analysis of risk for this investigation. Their selection was in part determined by the ecological receptors most likely adversely affected by a particular species transfer, e.g., disease agents of fish and wildlife, and would potentially adversely affect vulnerable species in the receiving area. Regardless of whether species occurrence in Souris River basin would reflect an expansion in species distribution or if the species currently occurs in both Missouri River and Red River basins of North Dakota, good measurement endpoints are intended to correspond to or are predictive of the selected assessment endpoints. The conceptual model establishes links between assessment endpoints and measurement endpoints. For the present study, our focus on invasive species or species having otherwise adversely effected receptors expedites the identification of measures of adverse effects, and their linkage to assessment endpoints ensures a technically founded transition between risk and biological consequences (see USGS 2005a).

2.2.2. Identifying biota of concern, pathways, and systems at-risk in NAWS. In USGS (2005a), estimates of biota transfer risks had been derived from categorical and quantitative analysis and were characterized with respect to their attendant uncertainties. A narrative analysis of pathways and their potential derivative risks were also considered, with a particular focus on biota of concern lacking data sufficient to more quantitative estimates of risks. Overall, risks of biota transfers varied across representative species of concern and followed a priority risk ranking as

Cyanobacteria

$\vee$

Waterborne disease agents

$\vee$

Aquatic and terrestrial-wetland plants

$\vee$

Aquatic invertebrates

$\vee$
$\vee$

Fishes

that suggested transfers of cyanobacteria (or their toxins) and waterborne disease agents would be associated with greater risks than other candidate biota of concern, particularly if control systems were not incorporated into water diversion processes and infrastructure. Additionally, in simulation studies, USGS (2005a) observed that risks of biota transfers under such controlled, closed-conveyance scenarios would range from low to very low (10^{-6} to 10^{-9} and less than 10^{-9}, respectively). The range of probabilities in the latter, very-low risk category would reach extremely lower levels in scenarios where stochasticity in the biota transfer process was fully captured. Low probability-high consequence events remained as risk management concerns, even under the most controlled engineering practice implemented for an interbasin water transfer or under the RRVWS no-action alternative (see USGS 2005a). Risks were greatest when interbasin water diversions were envisioned as being implemented via open conveyance, and greatest risk reduction was achieved when source waters were treated (e.g., using combined control technologies such as conventional water treatment and pressure-driven membrane filtration) within the exporting basin then transferred via closed conveyance (e.g., piped transfer) to importing basin (see Appendix 1 for brief summary of USGS 2005a,b, 2006).

Biota of concern for the NAWS project. In view of these technical findings, the selection of representative species of concern in the RRVWS project captured the range of biota potentially available for emigration from the Missouri River to Souris River basin in the NAWS project. Given the common concerns characterizing the NAWS and RRVWS projects, biota of concern for the NAWS project were identified as those representative species that had been characterized as high-priority species in outcomes from the risk analysis for the RRVWS project (Table 2).

Pathways and systems at-risk. USGS/CERC had completed a 3-report series focused on biota transfer issues associated with interbasin water diversions proposed as part of the RRVWS project (USGS 2005a,b, 2006). That analysis of risks associated with potential biota transfers between Missouri River and Hudson Bay basins had yielded multiple, complimentary outcomes derived from a range of analytical tools to evaluate risks and risk-reduction measures considered in the RRVWS project as it developed. As such, pathways and systems at-risk for biota transfers associated with water resource management activities linked to proposed activities in NAWS shared common attributes to those predicating conditions in RRVWS. Hence, integration of pathways and systems at-risk for NAWS captured predicating conditions critical to the analysis of risks (e.g., potential linkage of sources and receptors via pathways) similar to RRVWS. As with RRVWS project, the conceptual model developed for NAWS will be the primary outcome of Problem Formulation and help guide the analysis of risks for the project.

Pathways considered in developing the conceptual model for NAWS were common to those previously identified for RRVWS project (see USGS 2005a) and are summarized in Table 3. NAWS-specific pathways are relatively simple in their characterization, since the engineering infrastructure and water management practices bound the water transfer process potentially linked to unintended biota transfers between the Missouri River and Souris River basin. As in USGS (2005a), the analysis of risks in the current investigation discriminated between biota transfers linked to interbasin water diversions and those linked with other pathways within the context of competing risks, wherein biota transfer could be completed via any of potentially many pathways. From the perspective of competing risks, if biota transfer is considered a failure, then each of the many different ways that a failure can occur are competing for a successful outcome, e.g., a completed biota transfer or species invasion. For example, the series of events that predicate a success species invasion—dispersal followed by colonization and establishment of sustainable populations in newly occupied habitats—may be realized via different “flows-of-events” to achieve the end-state. These flows-of-events vary from being highly independent to highly dependent and interdependent processes (see USGS 2005a).

Table 2. Representative species that shaped the analysis of risks related to biota transfers linked to interbasin water diversions proposed for NAWS included the high ranking candidate species identified as biota of concern for the analysis of risks for the RRVWS project (see USGS 2005a).

Microorganisms and Infectious Diseases

Enteric redmouth
Infectious hemtopoietic necrosis virus (IHNV)
Escherichia coli (various serotypes)*
Legionella spp.*
Salmonella spp. (including, but not limited, to *S. typhi*, *S. typhmurium*, other *Salmonella* serotypes, and other water-borne infectious diseases)*

Protozoa and Myxozoa

Myxosoma cerebralis (*Myxobolus cerebralis*)
Polypodium hydriforme
*Cryptosporidium parvum**
*Giardia lamblia**

Cyanobacteria

*Anabaena flos-aquae**
*Microcystis aeruginosa**
*Aphanizomenon flos-aquae**

Biota associated with biosolids and sludge associated with interbasin water transfers, including:

- Potential transfer of plant and disease organisms (plant, wildlife, and human)
- Potential biota transfers derived from sludge and biosolid disposal

*Species distribution is cosmopolitan throughout North America, but species included as part of the analysis, given the relative importance of shifts in metapopulations that might be linked to, e.g., disease outbreaks.

Table 3. Illustrative list of pathways for biota transfers between Missouri River and Souris River basin.

Expansion of species distributions without human intervention (intentional or unintentional)

- Flooding to link basins otherwise providing barriers to dispersal
- Climate change promoting species expansions previously precluded by preferred species-habitat relationships

Expansion of species distributions mediated through human activities

- Intentional releases (malicious or otherwise)
- Unintentional
  - Associated with interbasin water transfers
  - Aquaculture practices (including fishes, aquatic invertebrates, and aquatic plants)
  - Aquarium trade and unintentional releases from captivity
  - Transfers linked to boat, ship, and barge management practices
    - Commercial
    - Recreational
  - Canals, locks, and channels as part of water management practices
  - Live bait an releases from recreational and commercial fisheries
  - Releases associated with other sources (e.g., food business) and disposal practices

As was the case for RRVWS, the analysis of risks focused on the engineering project envisioned in the DEIS for the NAWS project. As such, the conceptual engineering designs focused on water conveyance and treatment are summarized in the following section.

2.2.3 Alternatives considered in the DEIS for NAWS. The analysis of risks associated with biota transfers potentially linked to interbasin water diversions mediated through NAWS water management practices is strongly influenced by infrastructure proposed to serve water to the service area. Infrastructure can be considered in terms of conveyance (Section 2.2.4) and treatment (Section 2.2.5), as control system countermeasures targeted as risk reduction tools to offset biota transfer risks. Here, we simply consider the control system for delivering water from the Missouri River source at Lake Sakakawea to the water treatment plant at Minot, North Dakota as two components: (1) the existing closed conveyance structure (pipeline) and (2) the biota treatment system proposed as part of the control system mediating the interbasin water transfer.

2.2.4 Conveyance. For NAWS, the analysis and characterization of risks relied on previous work that focused on biota transfers between Missouri River and Red River in the Hudson Bay watershed (USGS 2006, 2005a,b). In contrast to that earlier work, however, the conveyance system is a shared attribute of all control systems conceptually designed and outlined in the DEIS being developed for NAWS (Reclamation 2007). Table 4 presents a summary of infrastructural attributes for the existing transmission pipeline. Figure 3 and Figure 4 capture

Table 4. Existing pipeline transmission system for NAWS (see Reclamation 2007).

Existing Pipeline

- Approximately 45 miles extending between Snake Creek Pumping Plant and Minot, ND
- Ductile Iron Pipe

Item	Quantity in Linear Feet (LF; SWC)[1]		Total LF	Miles
Contract 2-1A: 3.1 miles of 30" and 6.3 miles of 36" from the Minot WTP to the south				
30" Water Pipeline w/o Joint Restraint	12,402			
30" Water Pipeline w/ Joint Restraint	3,806	**Total 30"**	16,208	3.07
36" Water Pipeline w/o Joint Restraint	25,868			
36" Water Pipeline w/ Joint Restraint	7,426	**Total 36"**	33,294	6.31
Pipeline Isolation Valve	3			
Cathodic Protection				
Contract 2-1B: 2.8 miles of 30" and 6.7 miles of 36" from the end of contract 2-1A to the proposed 1 million gallon reservoir				
30" Water Pipeline w/ Joint Restraint	483			
30" Water Pipeline w/o Joint Restraint	14,102	**Total 30"**	14,585	2.76
36" Water Pipeline w/ Joint Restraint	1,764			
36" Water Pipeline w/o Joint Restraint	33,712	**Total 36"**	35,476	6.72
Cathodic Protection				
Contract 2-1C: 11.2 miles of 36" from the end of proposed reservoir location to Max, North Dakota				
36" Water Pipeline w/ Joint Restraint	783			
36" Water Pipeline w/o Joint Restraint	58,375	**Total 36"**	59,158	11.20
Cathodic Protection				
Contract 2-1D: 14.8 miles of 36" from Max, ND to Totten Trails (Lake Sakakawea)				
36" Water Pipeline w/ Joint Restraint	280			
36" Water Pipeline w/o Joint Restraint	77,958	**Total 36"**	78,238	14.82
Cathodic Protection				
		Summary		
			LF	**Miles**
		30" Pipe	30,793	5.83
		36" Pipe	206,166	39.05
		Total	236,959	44.88

[1]Source: North Dakota, State Water Commission

Figure 3. NAWS service area illustrating existing water transmission pipeline route.

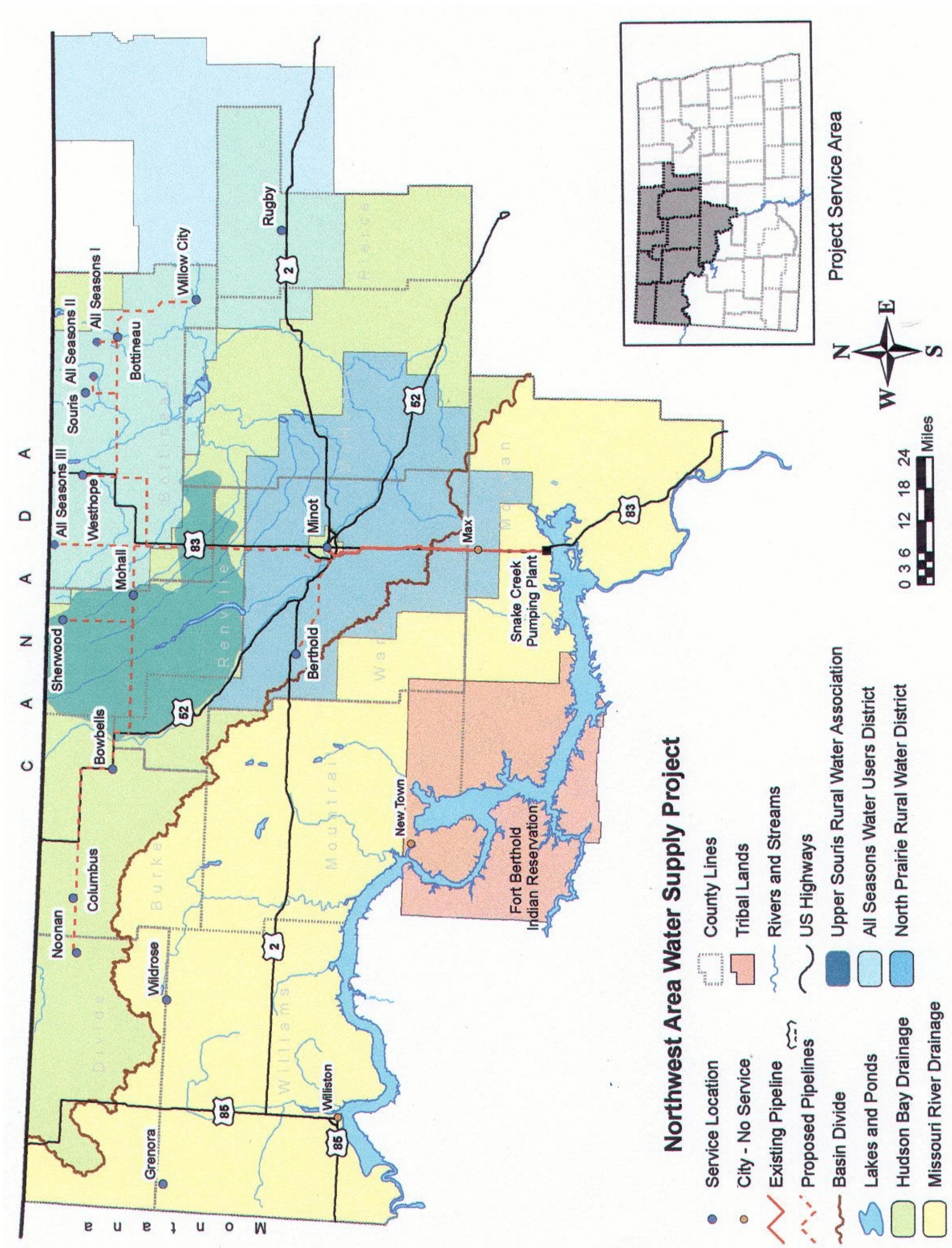
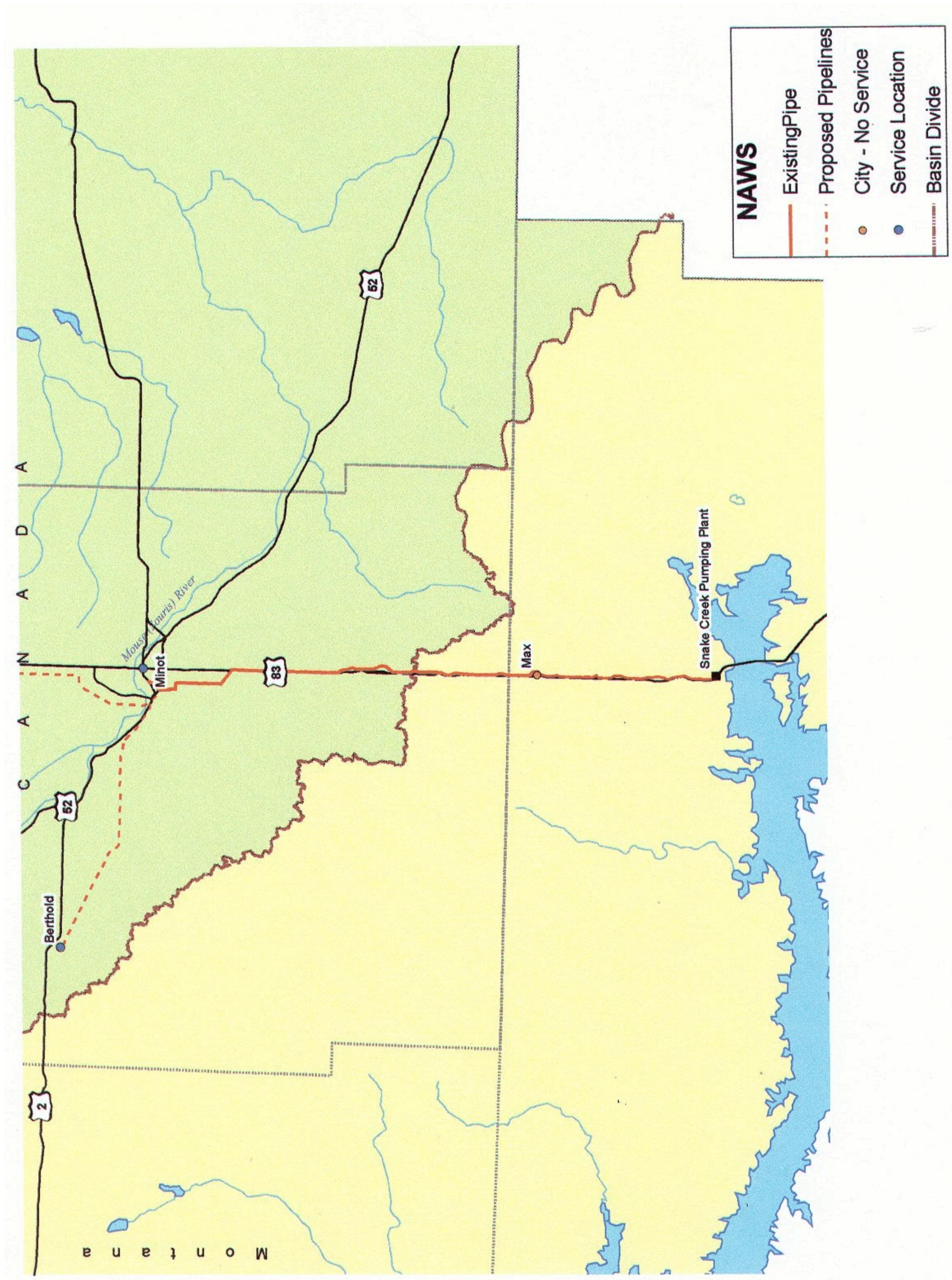


Figure 4. Water transmission pipeline shadows Highway 83 north from Lake Sakakawea to Minot, North Dakota lying 45 miles to the north.



the spatial attributes for the conveyance system as it is currently configured. In addition to these tabular and graphic illustrations, a series of remotely collected images are included in Figure 5A-Z, wherein the pipeline route is traced from the north terminus at the Minot, North Dakota water treatment plant (WTP) to the south terminus at Lake Sakakawea.

2.2.5 Treatment Alternatives for the NAWS EIS. NAWS is a MR&I project to deliver water from the Missouri River to cities and rural water systems in northwestern North Dakota. The project has a maximum capacity of 26 million gallons per day (MGD). Four biota treatment alternatives are currently being considered in the DEIS being prepared by Reclamation (see Table 5).

Table 5. Summary of conceptual designs of water treatment operations that are being considered for interbasin water diversion potentially achieved as part of NAWS project.

Alternative	Step 1	Step 2	Step 3	Step 4	Continental Divide	Step 5
A	Chlorination-Chloramination					Minot WTP
B	Coagulation-Flocculation-Sedimentation	UV Treatment	Chlorination-Chloramination			Minot WTP
C	Dissolved Air Flotation	Media Filtration	UV Treatment	Chlorination-Chloramination		Minot WTP
D	Pre-treatment	Microfiltation	UV Treatment	Chlorination-Chloramination		Minot WTP

Alternative A: Chemical Treatment. The Chemical Treatment alternative or the “no action alternative” was originally proposed in the *Environmental Assessment* (Houston Engineering et al. 2001) and *Finding of No Significant Impact* for the NAWS project (Reclamation 2001). This alternative is not intended to meet requirements under the Safe Drinking Water Act (SDWA) until source waters have been treated in Minot. The alternative was designed to provide biota control through disinfection at the source using combined chlorine-chloramine pre-treatments, where a chloramine residual would be maintained in the pipe for control of biofilm. The pre-treatment facility would provide 3-log inactivation of *Giardia* and 4-log inactivation of viruses prior to crossing the watershed boundary (see Houston Engineering et al. 1995a,b). The North Dakota Department of Health agreed that the pre-treatment facility would achieve the primary disinfection credit required and no primary disinfectant would be required at the water treatment plant (WTP) in Minot (Reclamation 2001).

Several mechanical and structural features and operational procedures will be built into this alternative (see Houston Engineering 1998, 2001). The final step in this proposed alternative includes final treatment to SDWA standards at an upgraded facility in Minot, currently envisioned as a process including conventional lime softening with ultraviolet (UV) irradiation proposed for disinfection (Reclamation 2001a).

Alternative B: Basic Treatment. Alternative B includes a conventional coagulation-flocculation-sedimentation process in series with UV irradiation, chlorine disinfection, and chloramine residual at the source. The final treatment process would occur at the Minot WTP. As proposed, this process would consist of a pumped flash-mix[4] facility and a partially buried concrete basin for coagulation, flocculation, and sedimentation. Source waters would then be UV disinfected and chloramines added to provide residuals before being transferred from the Missouri River basin (HUC10) into the Souris River subbasin (HUC0901) of the Red River basin (HUC 09).

Alternative C: Dissolved air flotation (DAF) and Media Filtration. Alternative C included a Dissolved Air Flotation (DAF) pre-treatment followed by media filtration, UV disinfection, and chlorine treatment and chloramine addition to maintain chlorine residual in the treated waters. This alternative would provide water in compliance with SDWA immediately upon leaving the treatment facility. Conventional lime softening would occur at the Minot WTP.

Alternative D: Microfiltration. To provide a full range of alternatives for biota treatment, a membrane filtration alternative—microfiltration—has also been included for this analysis. Membrane filtration provides a practically absolute barrier to particles passing through the control system. From a regulatory perspective, membrane filtration is granted substantial log removal credit for *Giardia* and *Cryptosporidium*, depending on membrane of choice (see Section 3). Membrane alternatives would include a pre-treatment step dependent on the type and size of membrane technology specified in the control system's final design. Once biota treatment were completed at the source, this alternative could provide SDWA quality water immediately upon leaving the treatment facility. At Minot WTP the treated water would be softened using the facility's current processes.

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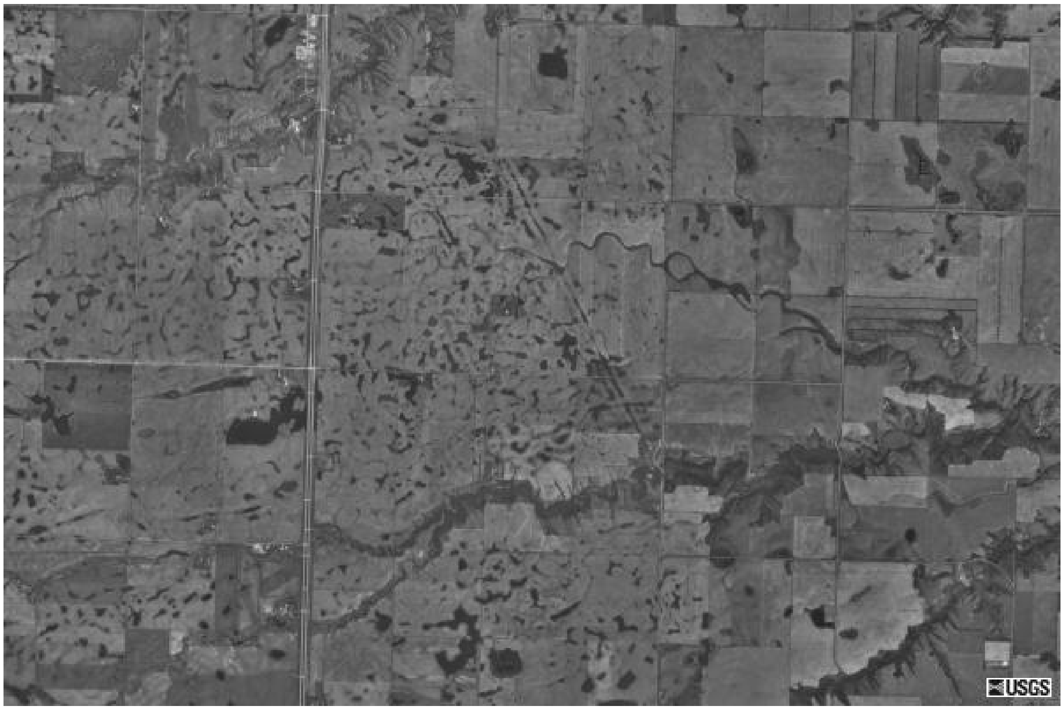
[4]The mixing of coagulant chemical and source waters is commonly referred to as flash mixing, with the primary purpose of the flash-mix process being to rapidly mix and equally distribute the coagulant chemical throughout source water. The reaction between the colloidal matter with the coagulating chemical occurs within seconds, resulting in formation of very small floc particles. As the floc clumps together, larger, heavier floc is formed which can settle out or be removed by filtration.

Figure 5. A series of remote images collected in May, 1995 provide a photographic tour of the water transmission pipeline route, retracing the path of water movement from its north terminus in Minot, North Dakota through the prairies adjacent to Highway 83 and ending at Lake Sakakawea. Landscapes along the pipeline course are prairie pothole habitats. (Source: USGS EROS photographic archive)

Figure 5A and 5B.

Figure 5C and 5D.

Figure 5E and 5F.



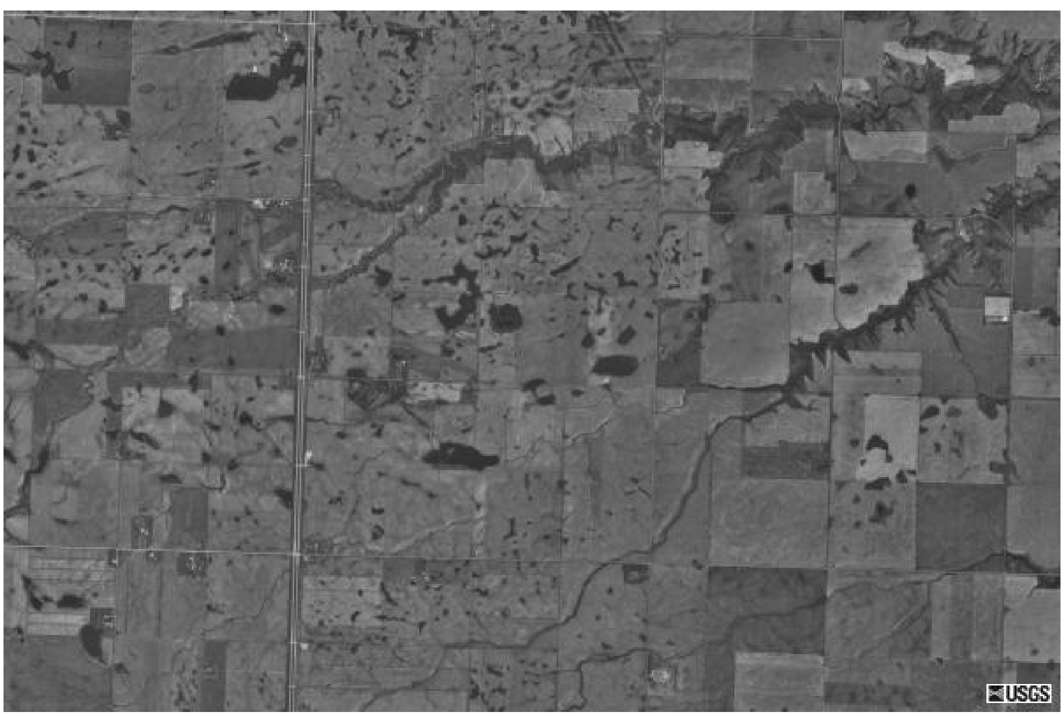


Figure 5G and 5H.

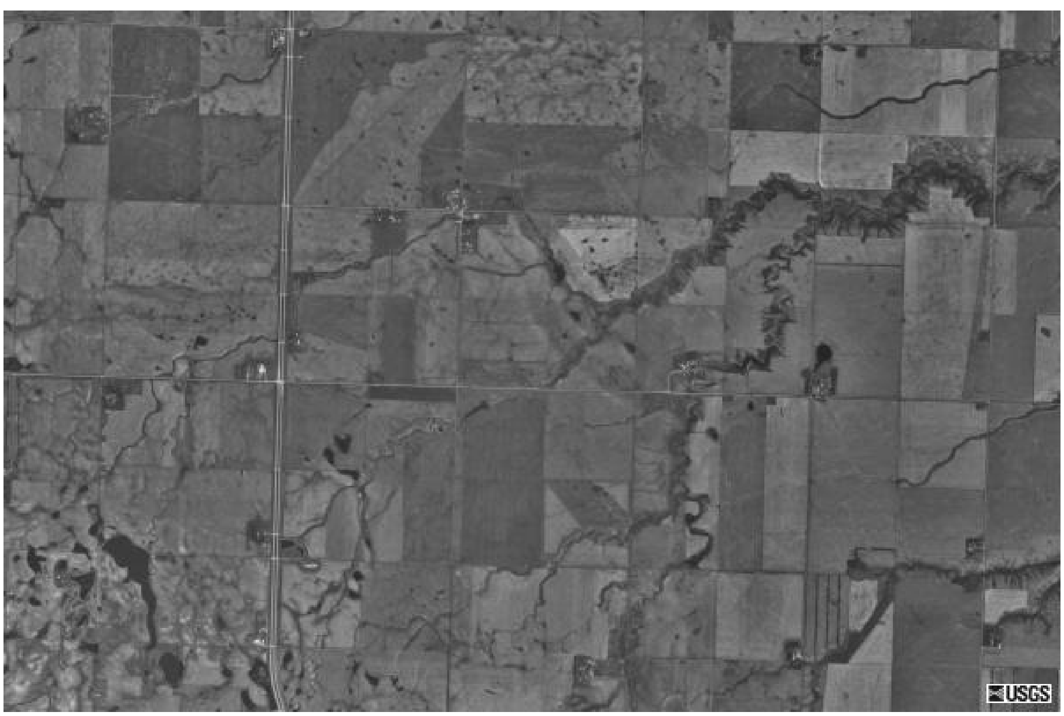
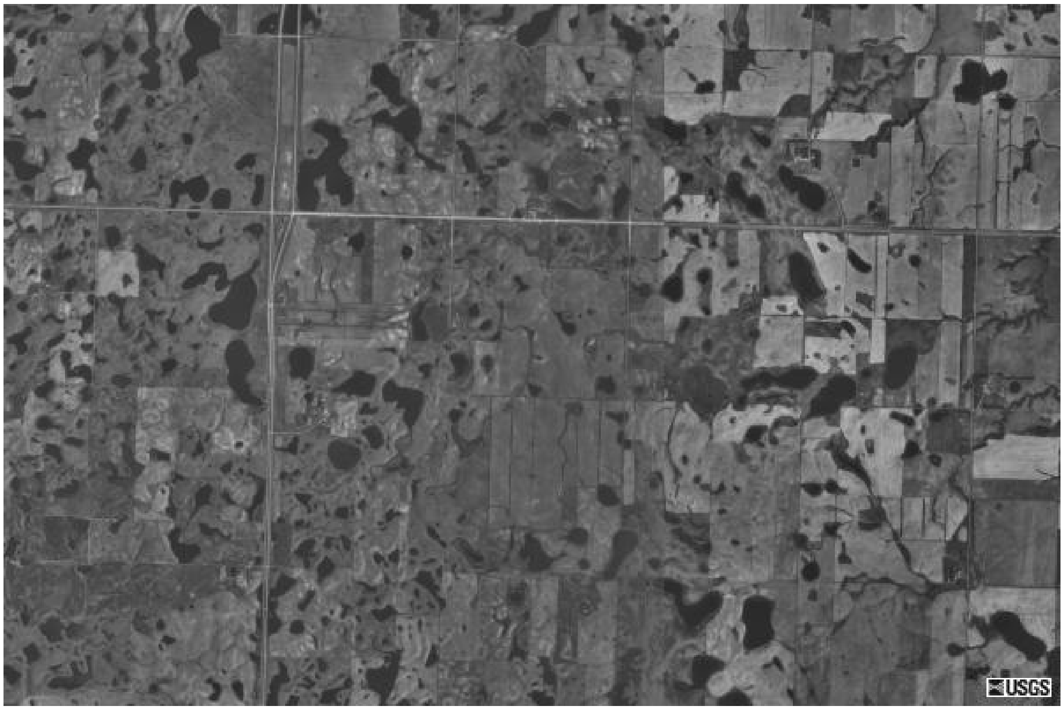


Figure 5I and 5J.

Figure 5K and 5L.



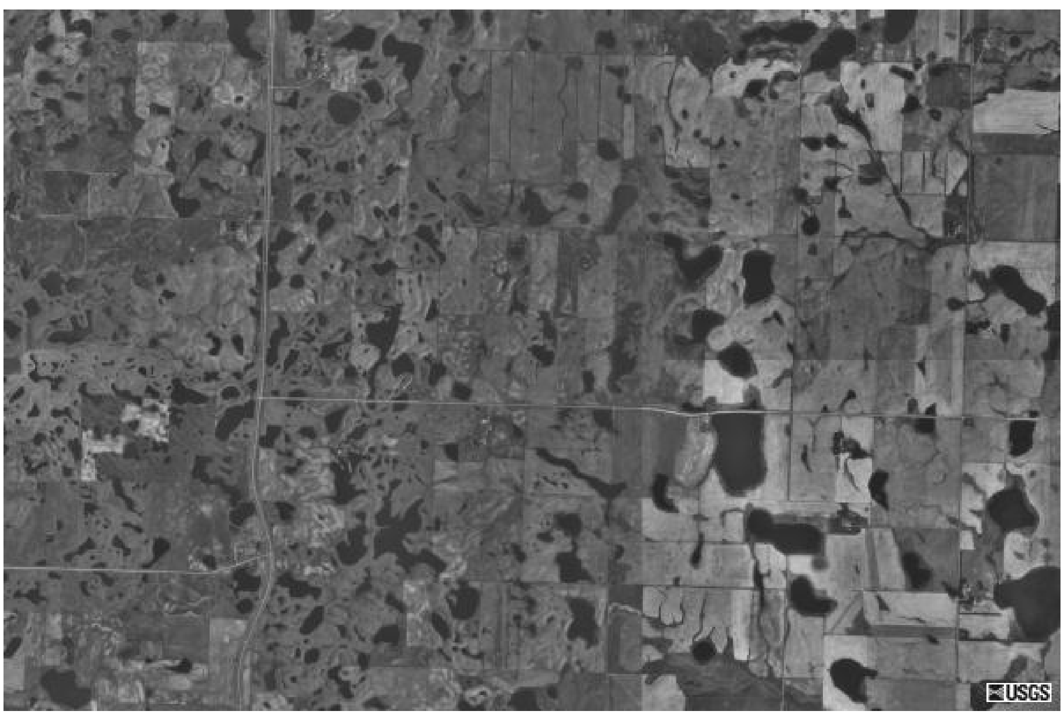
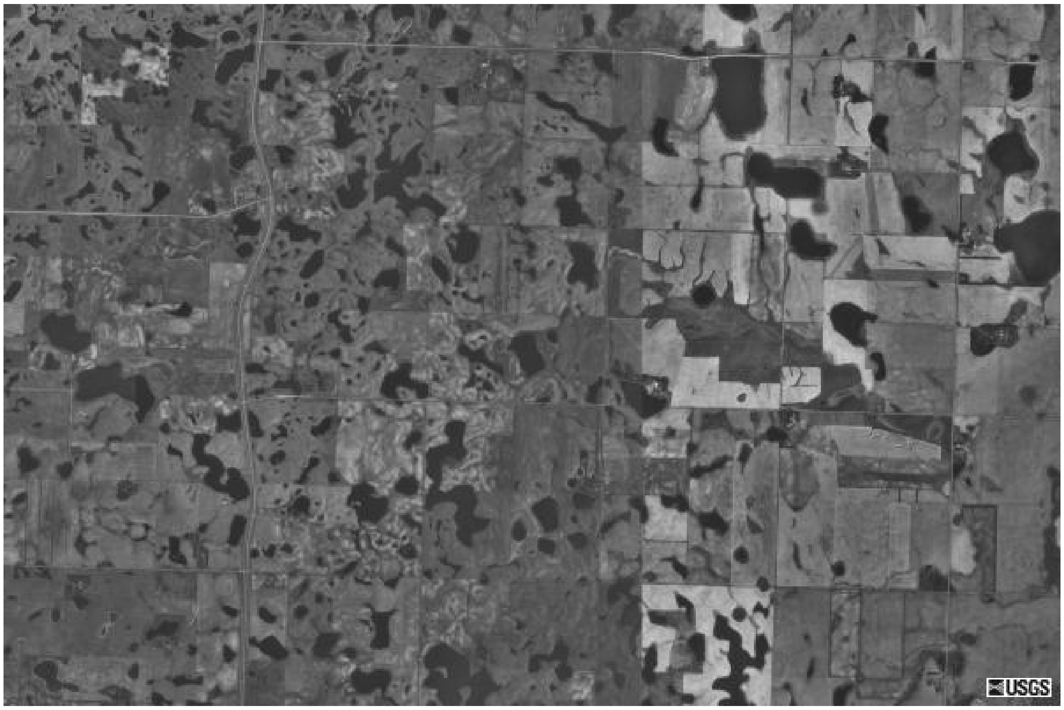


Figure 5M and 5N.



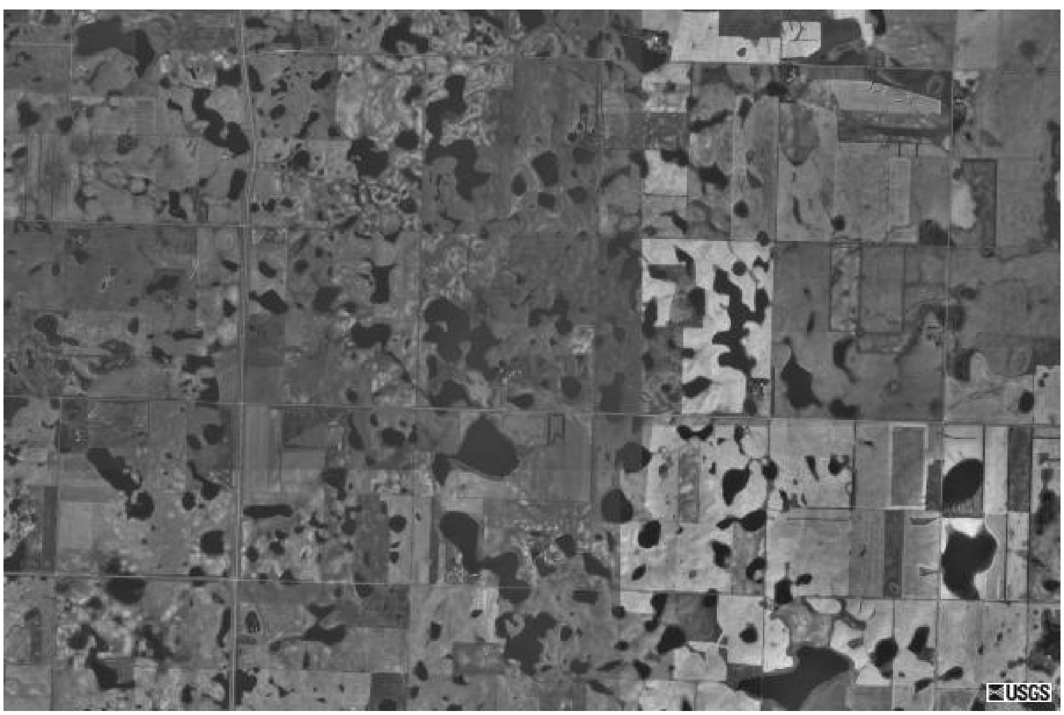
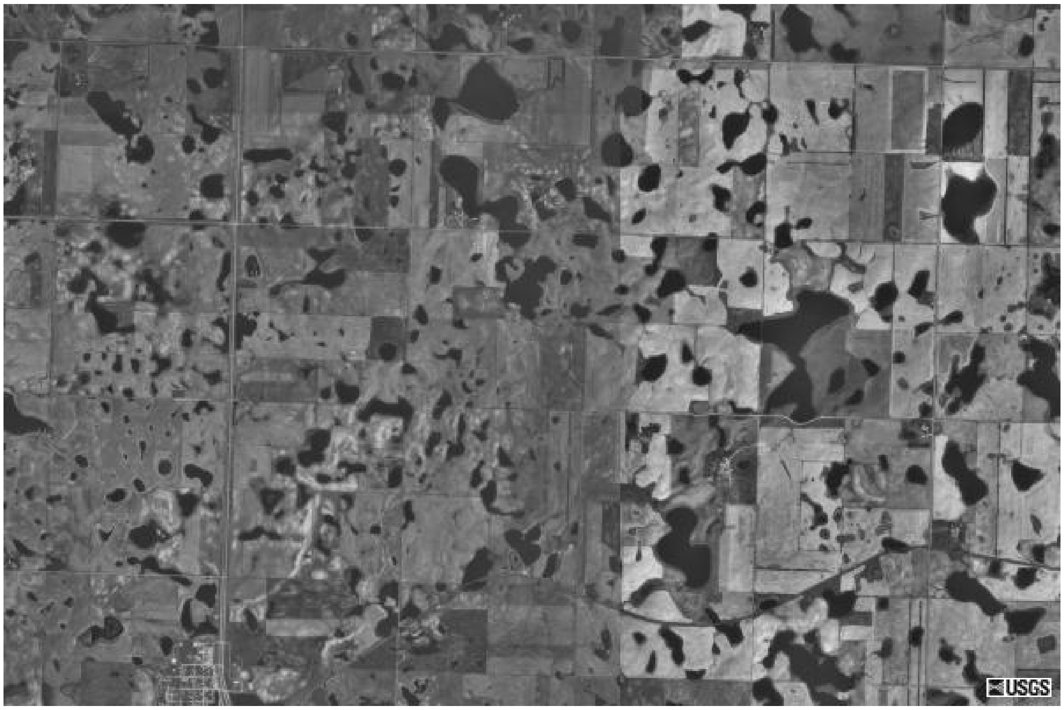


Figure 5O and 5P.



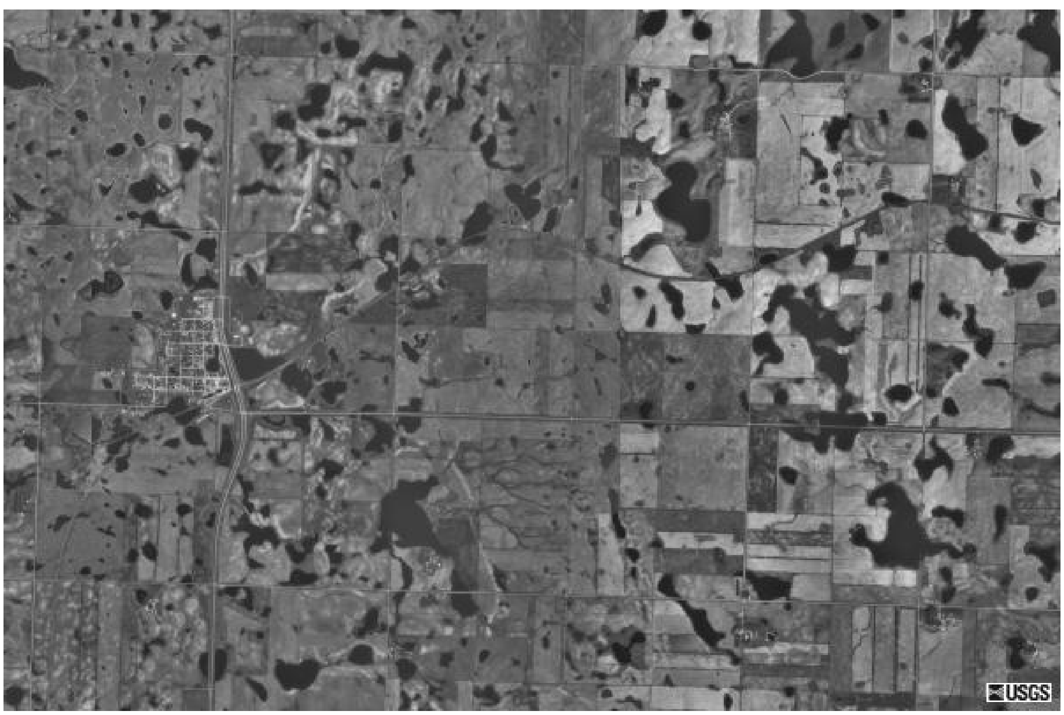
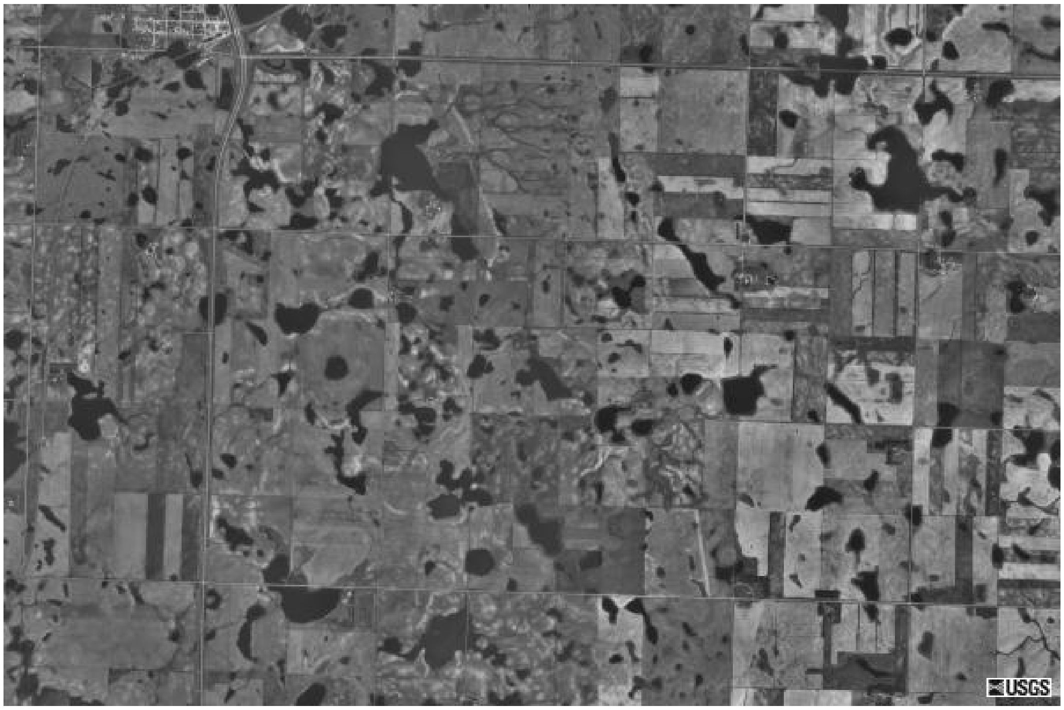


Figure 5Q and 5R.



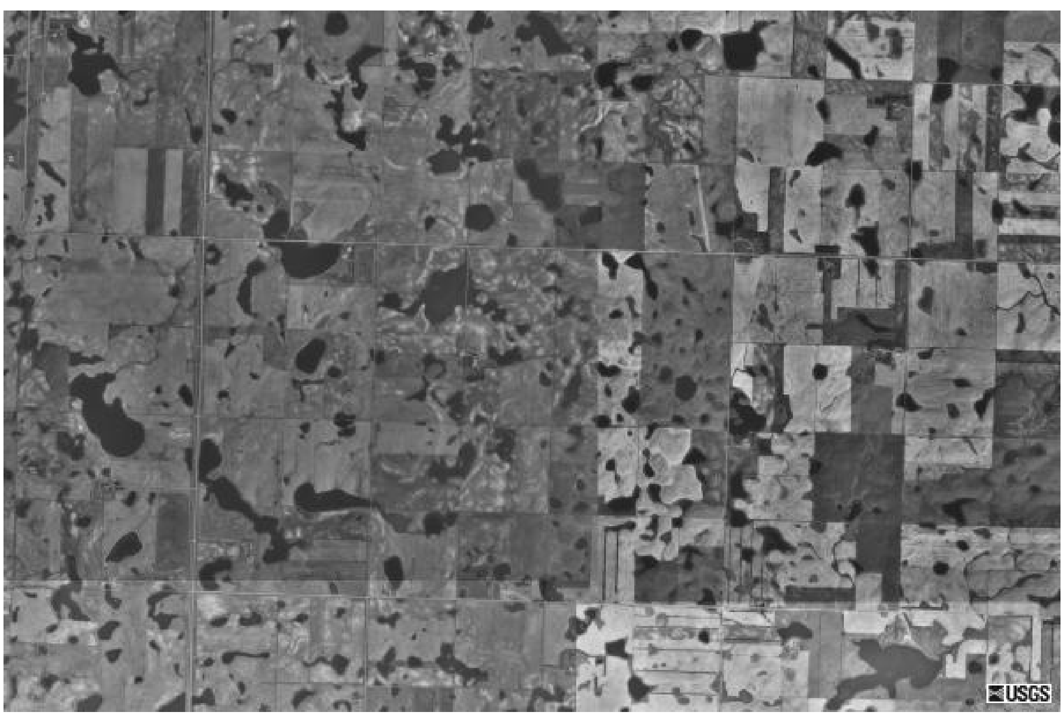
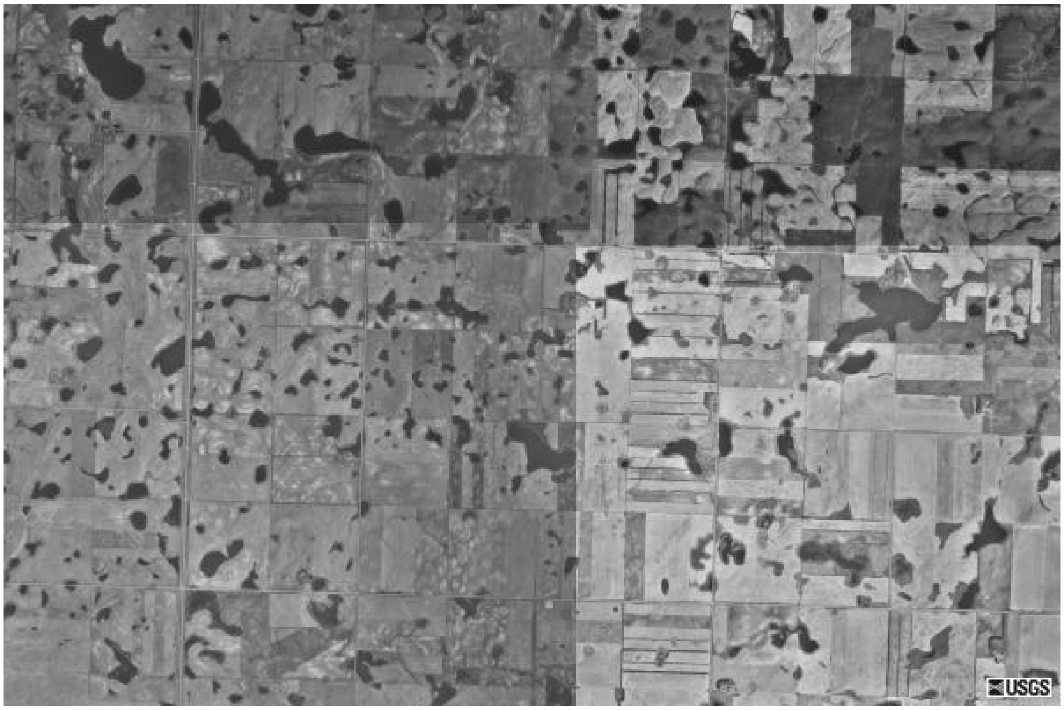


Figure 5S and 5T.



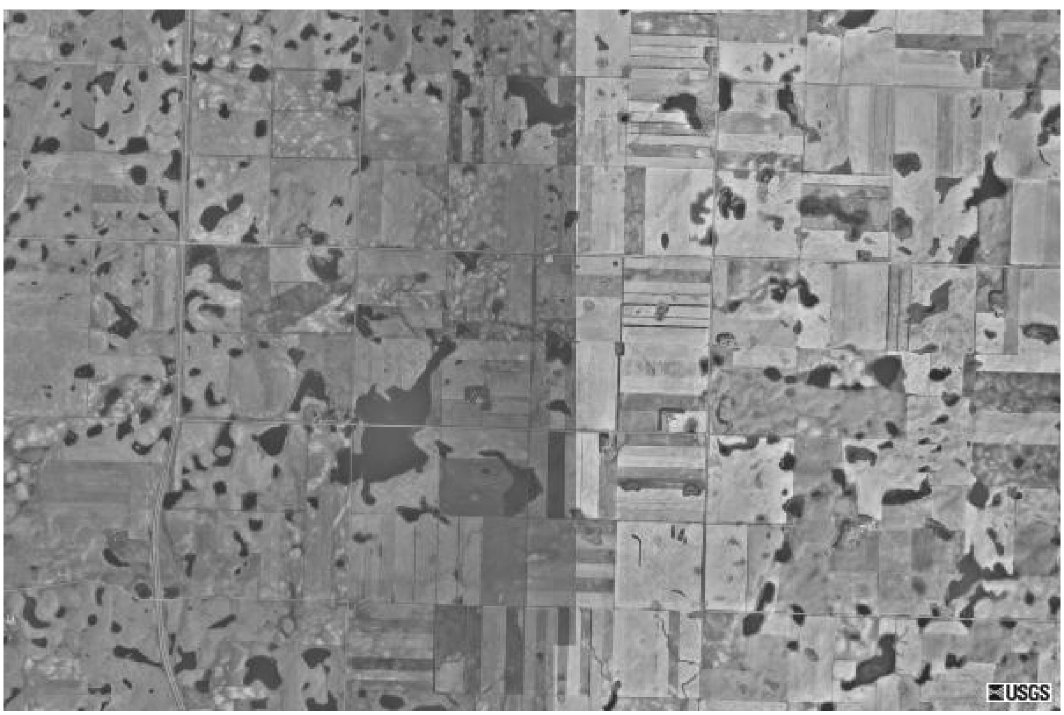
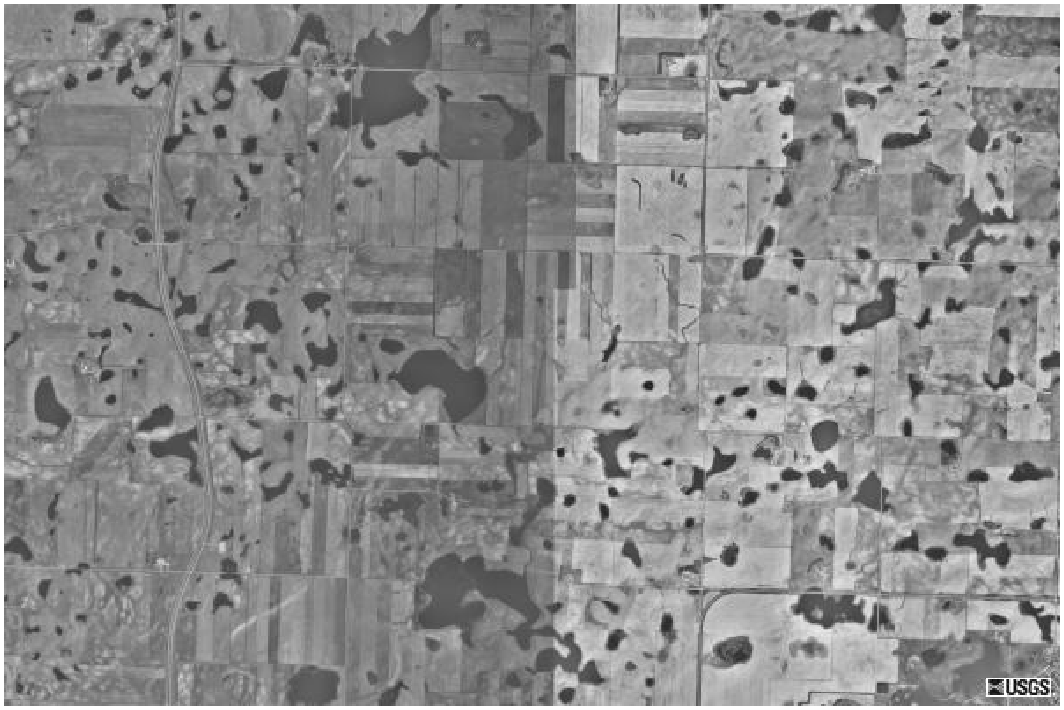


Figure 5U and 5V.



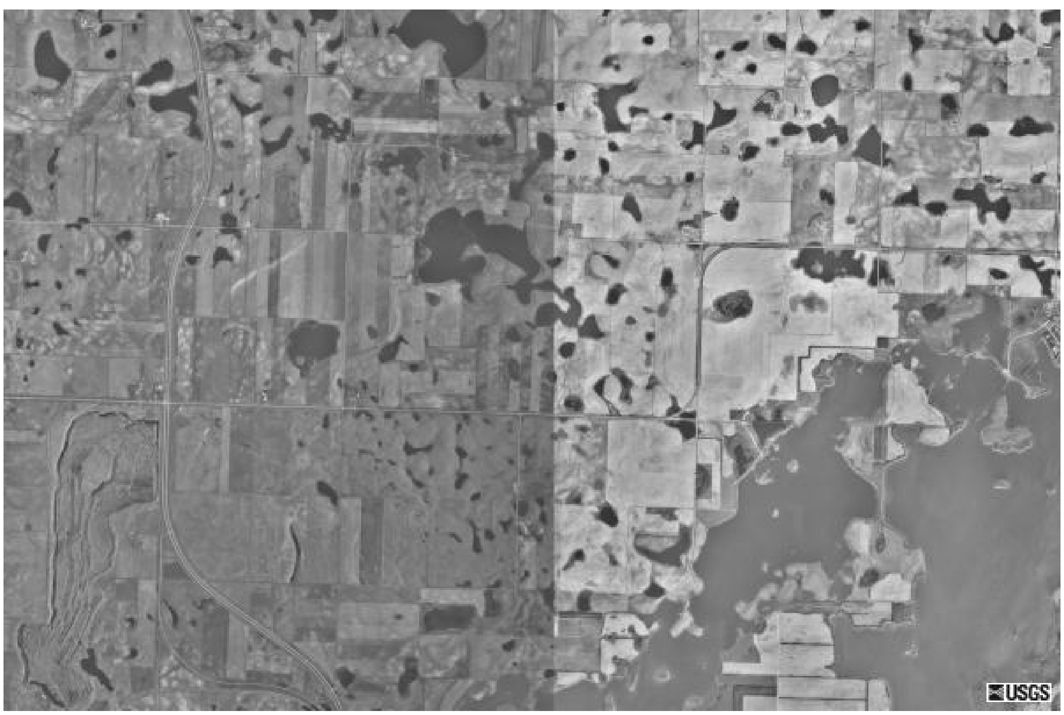


Figure 5W and 5X.

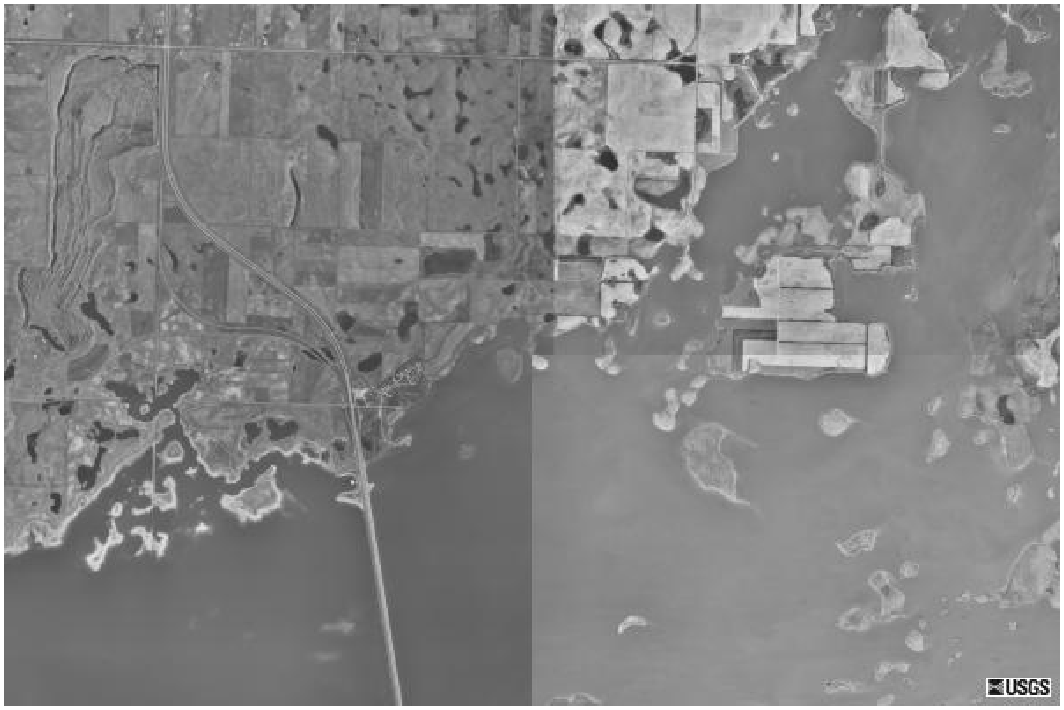
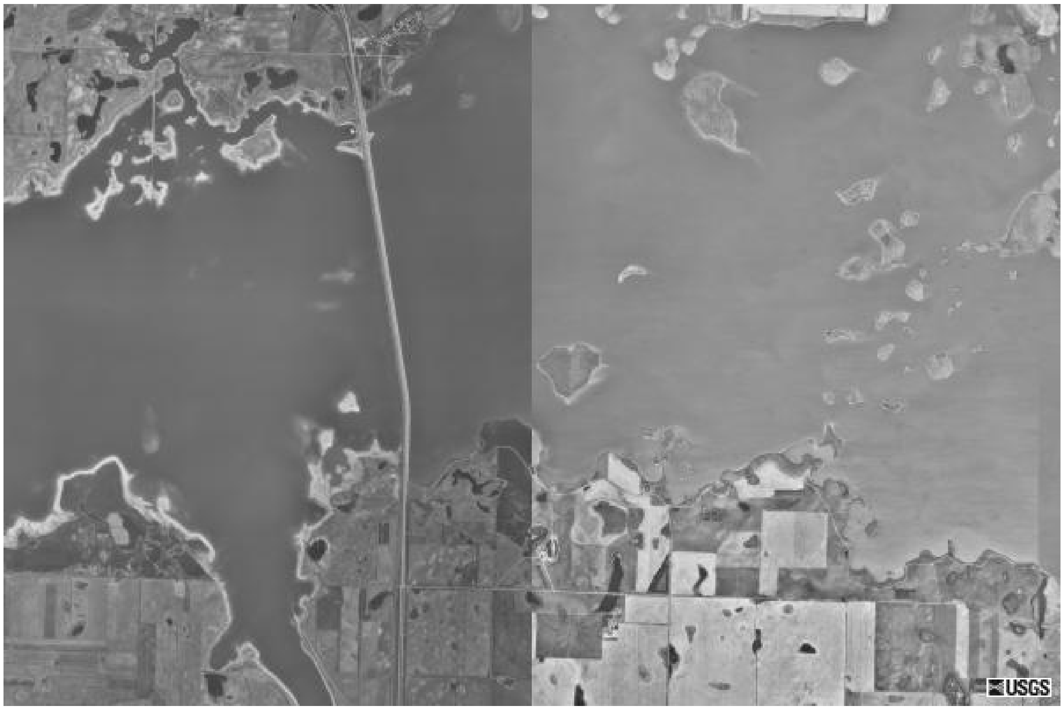
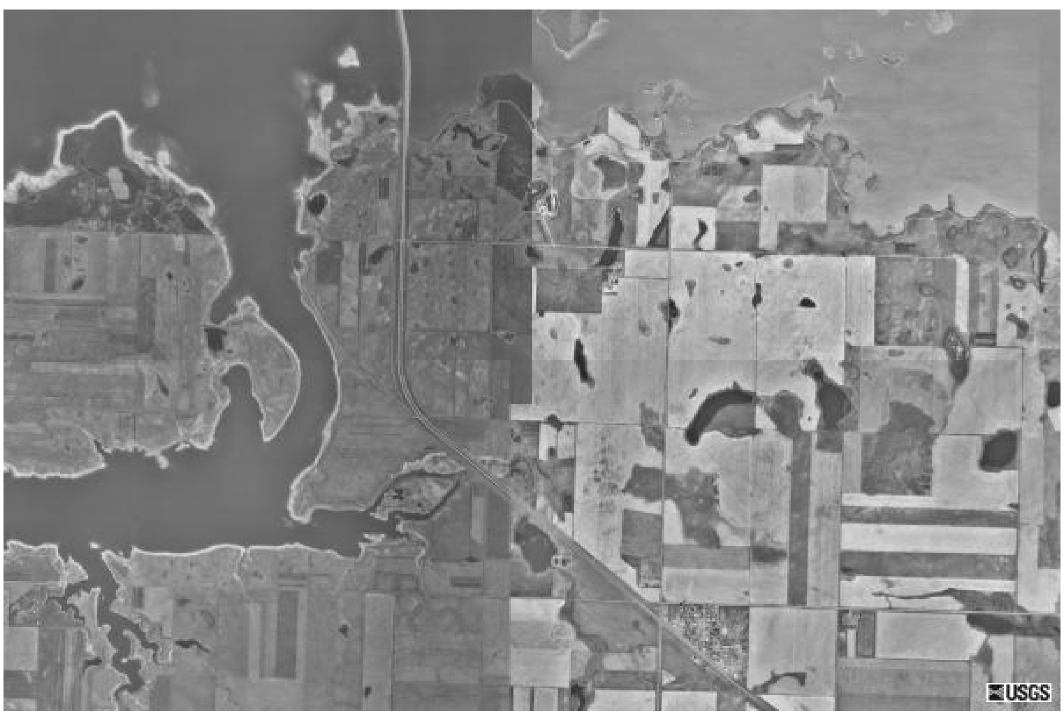


Figure 5Y and 5Z.





2.2.6 Environmental Setting and Systems At-Risk. The Souris River (also called, the Mouse River) drains portions of Saskatchewan, Montana, North Dakota, and Manitoba. As a subbasin (HUC 0901) within the Red River basin (HUC 09), the Souris River basin covers approximately 24,600-square-miles in southeast Saskatchewan, north-central North Dakota, and southwest Manitoba. The Souris River originates in the Yellow Grass Marshes north of Weyburn, Saskatchewan, then flows southeast, crossing the international boundary shared with North Dakota west of Sherwood. The river subsequently loops nearly 360 miles through north-central North Dakota, eventually returning to a northward flow and re-enters Canada west of the Turtle Mountains near Westhope, Manitoba. Within Canada, the river eventually reaches its confluence with the Assiniboine River near Brandon, Manitoba. Depending on the mapmaker, the Souris River basin occurs as a hydrological unit spatially comparable to the Assiniboine River basin (Figure 6) or occurs as a subbasin within a collective hydrological unit identified as the "Assiniboine River" basin that includes the Qu' Apelle River, Assiniboine River, and Souris River (Figure 7). Regardless of these differences in spatial presentation, in recent history the Souris River illustrates international efforts to manage water resources that defy political boundaries; for example, Souris River Bilateral Water Quality Monitoring Group was formed in 1989 by the governments of Canada and the United States and is responsible for documenting trends in water quality in the Souris River and making recommendations for monitoring future water-quality conditions (see http://nd.water.usgs.gov/pubs/wri/ wri004019/index.html last accessed May 21, 2007).

In North Dakota, the Souris River has seven major tributaries with the Des Lacs River contributing greatest inflows under nominal conditions. Hydrologically, the basin is poorly-integrated with 2,300 square miles considered as noncontributing to streamflow, a characteristic consistent with the topography across the subbasin which is varied, including hilly terrain in the southwest, flat glacial Souris Lake plain in the east, and forested hills of the Turtle Mountains in the northeast (Figure 8). Within the US, USGS identifies HUC09 as the Souris River-Red River-Rainy River hydrologic unit (Figure 9A, B, and C; see also Table 6), which consists of regions of the Souris River-Pembina River-Red River-Winnipeg River watersheds (Figure 6) or Assiniboine River-Red River-Winnipeg River watersheds (Figure 7). The Upper Souris, J. Clark Salyer, and Des Lacs National Wildlife Refuges are formed by shallow impoundments located on the Souris and Des Lacs Rivers and collectively retain greater than 350,000 acre-feet at maximum storage, which is equivalent to 88 percent of the total storage in the basin. Annual precipitation (mean) across the Souris River basin ranges from 13 inches in the west to 17 inches in the east. Figure 10 through Figure 17 provide a photographic travelogue of the Souris River in its passage through North Dakota.

For our present consideration, water use in the Souris River basin may be simply considered as that targeted for agriculture or municipal use. Ground waters supply over 40% of water destined for municipal use, with nearly 60% of the total water being used by irrigated agriculture. For irrigation, surface water sources contribute over 90% of water for irrigation purposes. Seasonal flooding along the tributaries of the Souris River—the Des Lacs and Wintering Rivers, and Ox, Oak, Willow, and Stone Creeks—can be problematic, especially for some communities in the basin such as Bottineau, Burlington, and Donnybrook. In addition to problems linked to season flooding, water quality within the Souris River Basin is a recurring

Figure 6. Watersheds as mapped by Prairie Provinces Water Board. (Source: Agriculture and Agri-Foods Canada)

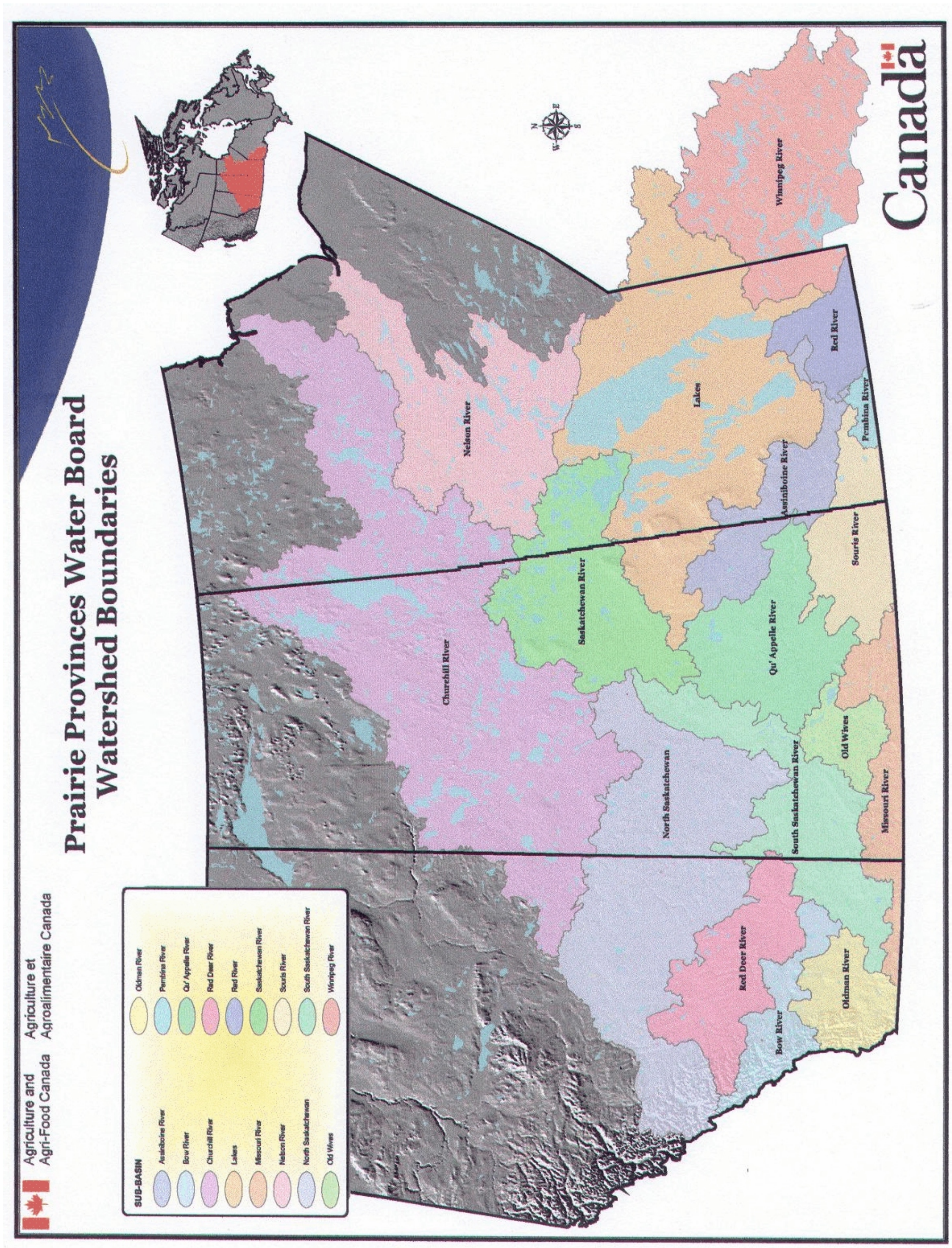


Figure 7. Major drainages in the northern Great Plains and Prairie Provinces. (Source: Manitoba Conservation)

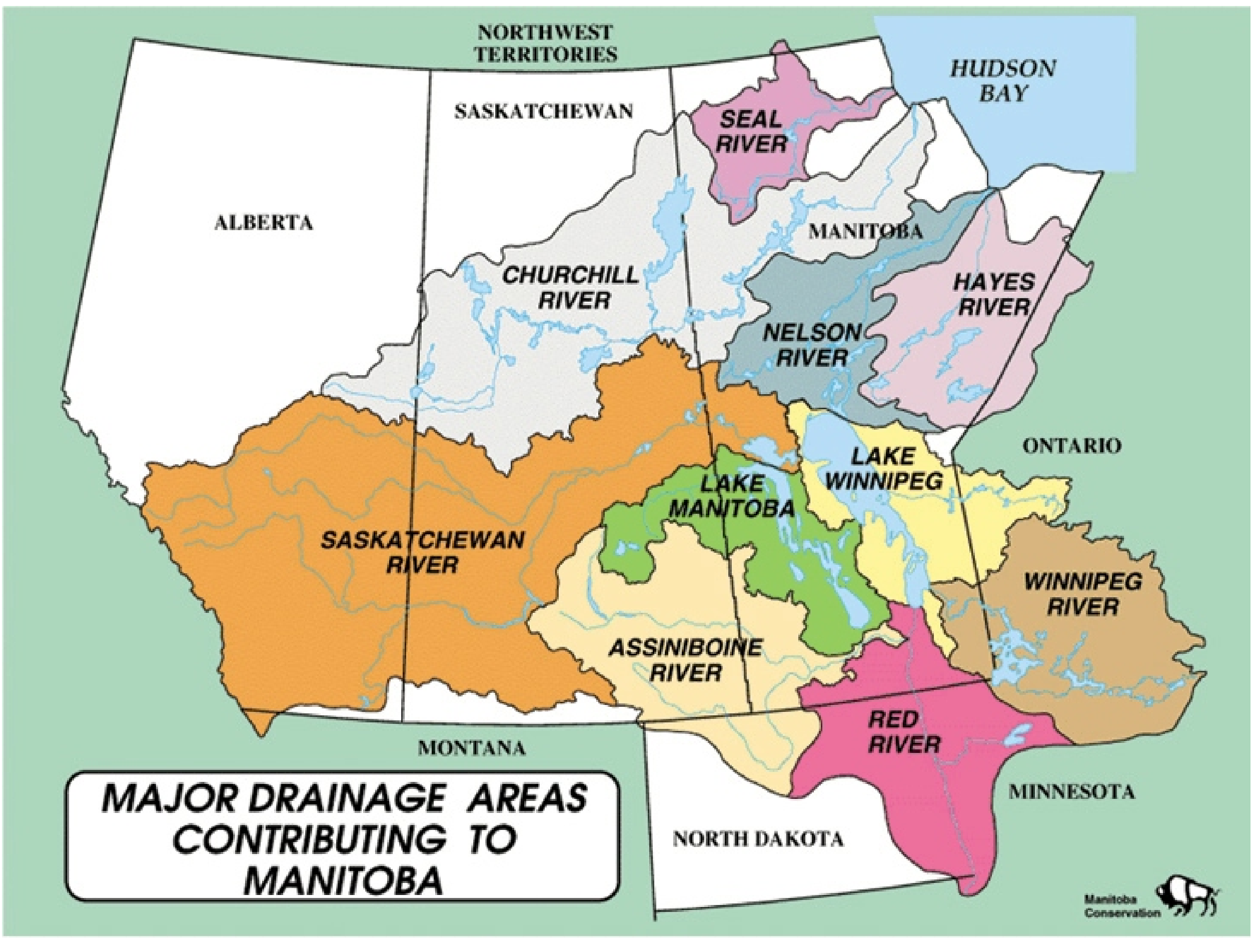


Figure 8. Physiographic regions of North Dakota.

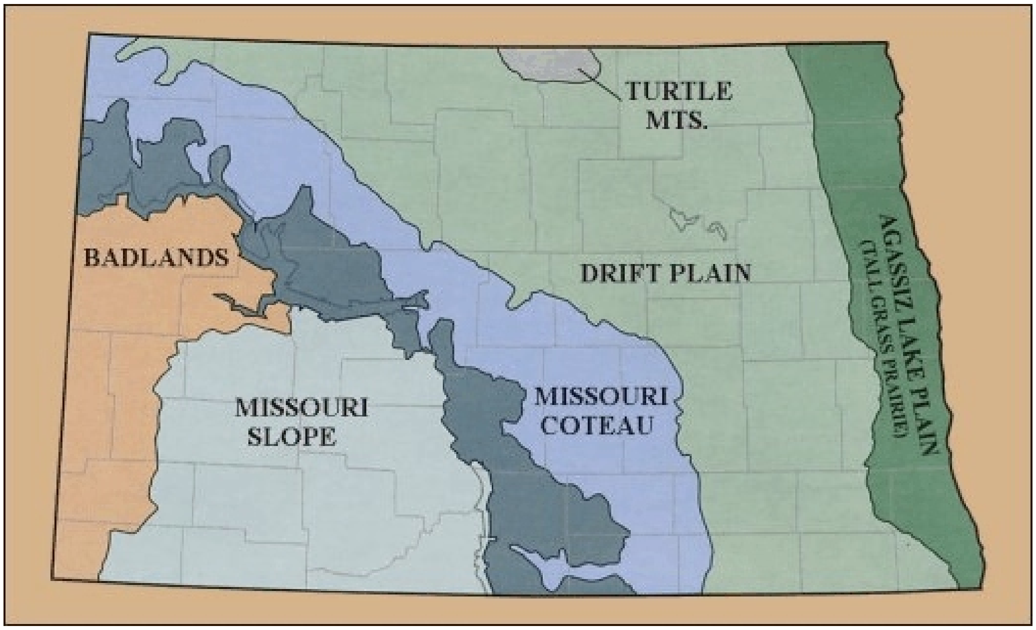


Figure 9A. Sub-basins (4-digit hydrological unit codes, HUCs) within Souris-Red River-Rainy River basin (HUC09).

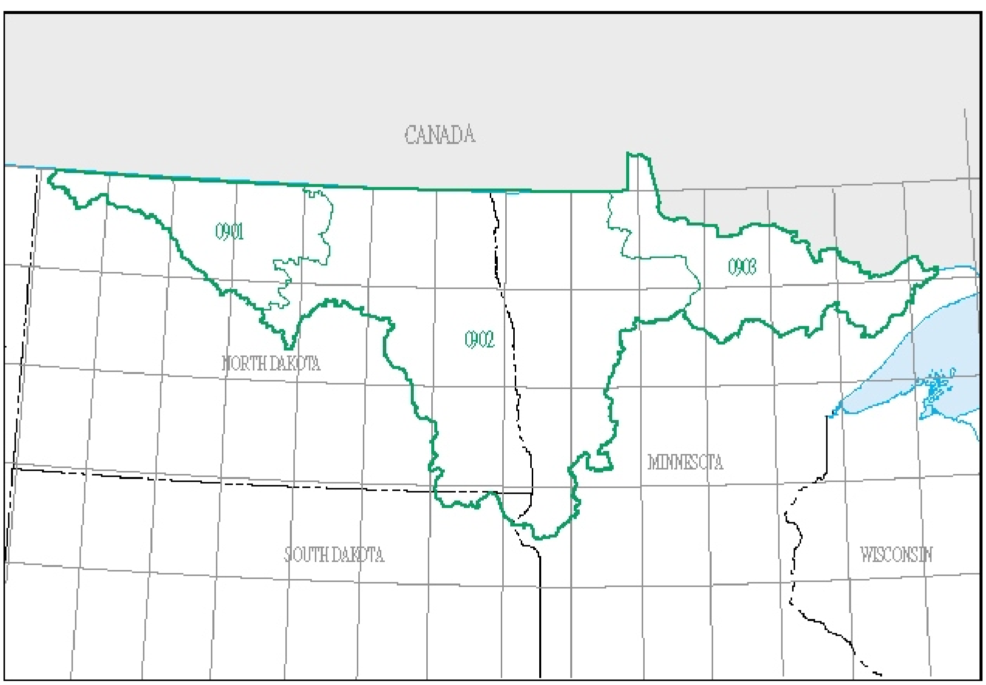


Figure 9B. Souris River basin (090100)

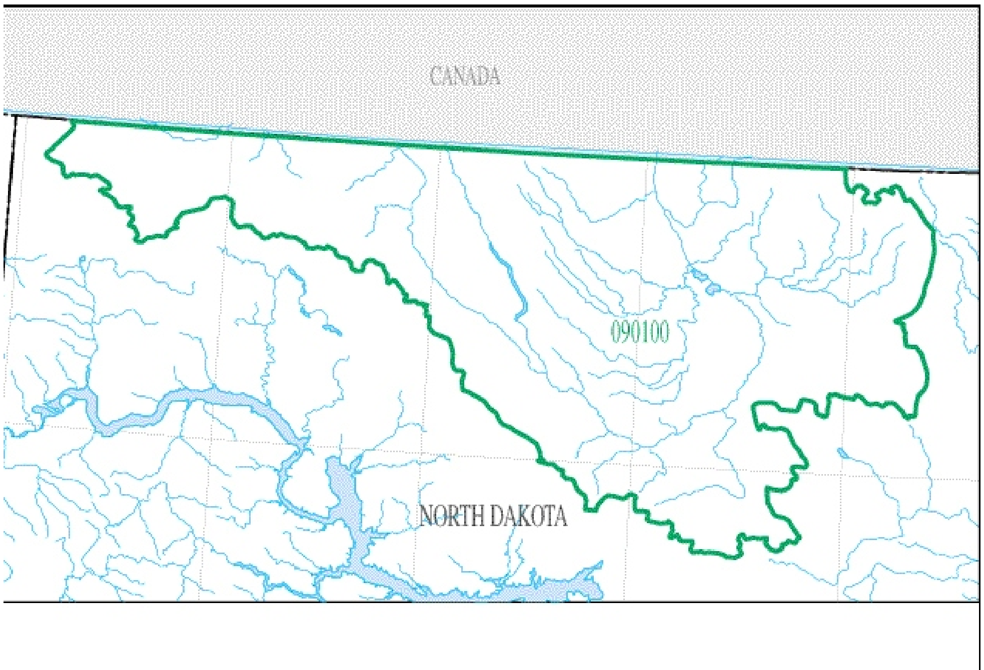


Figure 9C. Sub-basins (8-digit HUCs) within Souris River basin (see Table 6).

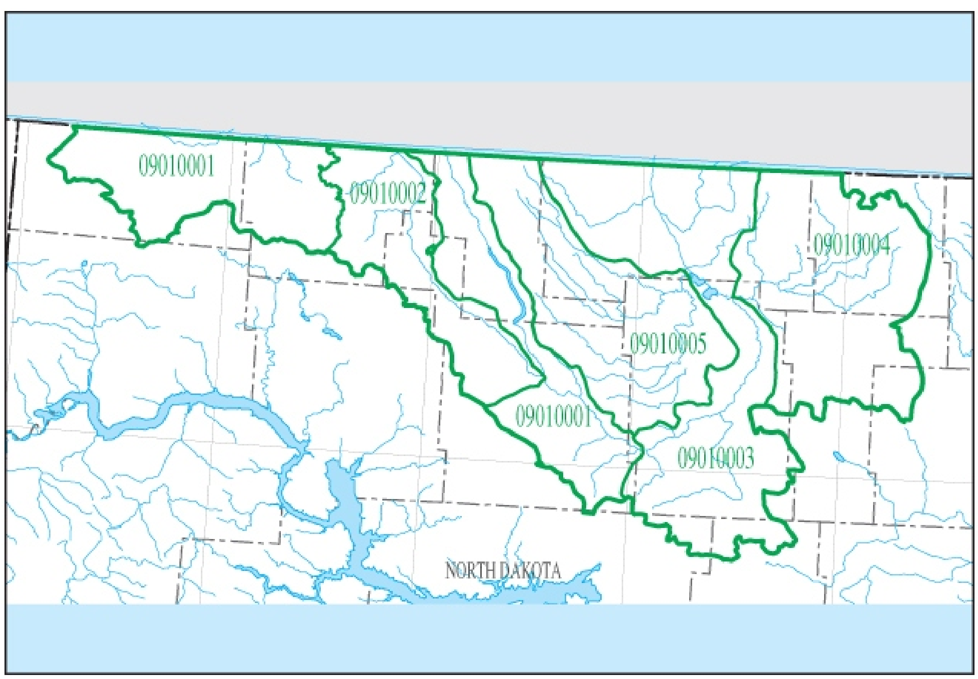


Table 6. ***Region 09 Souris-Red-Rainy Region.*** The drainage within the United states of the Lake of the Woods and the Rainy, Red, and Souris River Basins that ultimately discharges into Lake Winnipeg and Hudson Bay. Includes parts of Minnesota, North Dakota, and South Dakota.

Subregion 0901 -- Souris: The Souris River Basin within the United States. North Dakota. Area, 9150 sq.mi.

Accounting Unit 090100 -- Souris. North Dakota. Area, 9150 sq.mi.

Cataloging Units

09010001 -- Upper Souris. North Dakota. Area, 2340 sq.mi.
09010002 -- Des Lacs. North Dakota. Area, 1030 sq.mi.
09010003 -- Lower Souris. North Dakota. Area, 2260 sq.mi.
09010004 -- Willow. North Dakota. Area, 1850 sq.mi.
09010005 -- Deep. North Dakota. Area, 1670 sq.mi.

Subregion0902 -- Red: The Red River Basin within the United States including the Devils Lake closed basin. Minnesota, North Dakota, South Dakota. Area, 39800 sq.mi.

Accounting Unit 090201 -- Upper Red: The Red River Basin above the confluence of and including the Goose and Marsh River Basins, excluding the Sheyenne River Basin and the Devils Lake closed basin. Minnesota, North Dakota, South Dakota. Area, 12200 sq.mi.

Cataloging Units

09020101 -- Bois De Sioux. Minnesota, North Dakota, South Dakota. Area, 1140 sq.mi.
09020102 -- Mustinka. Minnesota. Area, 825 sq.mi.
09020103 -- Otter Tail. Minnesota. Area, 1980 sq.mi.
09020104 -- Upper Red. Minnesota, North Dakota. Area, 594 sq.mi.
09020105 -- Western Wild Rice. North Dakota, South Dakota. Area, 2380 sq.mi.
09020106 -- Buffalo. Minnesota. Area, 1150 sq.mi.
09020107 -- Elm-Marsh. Minnesota, North Dakota. Area, 1150 sq.mi.
09020108 -- Eastern Wild Rice. Minnesota. Area, 1670 sq.mi.
09020109 -- Goose. North Dakota. Area, 1280 sq.mi.

Accounting Unit 090202 -- Devils Lake-Sheyenne: The Sheyenne River Basin and the Devils Lake closed basin drainage. North Dakota. Area, 11000 sq.mi.

Cataloging Units

09020201 -- Devils Lake. North Dakota. Area, 3700 sq.mi.
09020202 -- Upper Sheyenne. North Dakota. Area, 1940 sq.mi.
09020203 -- Middle Sheyenne. North Dakota. Area, 2070 sq.mi.
09020204 -- Lower Sheyenne. North Dakota. Area, 1640 sq.mi.
09020205 -- Maple. North Dakota. Area, 1620 sq.mi.

Table 6. ***Region 09 Souris-Red-Rainy Region.*** The drainage within the United states of the Lake of the Woods and the Rainy, Red, and Souris River Basins that ultimately discharges into Lake Winnipeg and Hudson Bay. Includes parts of Minnesota, North Dakota, and South Dakota.

Accounting Unit 090203 -- Lower Red: The Red River Basin within the United States below the confluence of the Goose and Marsh River Basins. Minnesota, North Dakota. Area, 16600 sq.mi.

Cataloging Units

09020301 -- Sandhill-Wilson. Minnesota, North Dakota. Area, 1130 sq.mi.
09020302 -- Red Lakes. Minnesota. Area, 2040 sq.mi.
09020303 -- Red Lake. Minnesota. Area, 1450 sq.mi.
09020304 -- Thief. Minnesota. Area, 994 sq.mi.
09020305 -- Clearwater. Minnesota. Area, 1350 sq.mi.
09020306 -- Grand Marais-Red. Minnesota, North Dakota. Area, 482 sq.mi.
09020307 -- Turtle. North Dakota. Area, 714 sq.mi.
09020308 -- Forest. North Dakota. Area, 875 sq.mi.
09020309 -- Snake. Minnesota. Area, 953 sq.mi.
09020310 -- Park. North Dakota. Area, 1080 sq.mi.
09020311 -- Lower Red. Minnesota, North Dakota. Area, 1320 sq.mi.
09020312 -- Two Rivers. Minnesota. Area, 958 sq.mi.
09020313 -- Pembina. North Dakota. Area, 2020 sq.mi.
09020314 -- Roseau. Minnesota. Area, 1230 sq.mi.

Subregion0903 -- Rainy: The Rainy River Basin and Lake of the Woods drainage within the United States. Minnesota.
Area, 11400 sq.mi.

Accounting Unit 090300 -- Rainy. Minnesota. Area, 11400 sq.mi.

Cataloging Units

09030001 -- Rainy Headwaters. Minnesota. Area, 2540 sq.mi.
09030002 -- Vermilion. Minnesota. Area, 1080 sq.mi.
09030003 -- Rainy Lake. Minnesota. Area, 908 sq.mi.
09030004 -- Upper Rainy. Minnesota. Area, 529 sq.mi.
09030005 -- Little Fork. Minnesota. Area, 1880 sq.mi.
09030006 -- Big Fork. Minnesota. Area, 2070 sq.mi.
09030007 -- Rapid. Minnesota. Area, 867 sq.mi.
09030008 -- Lower Rainy. Minnesota. Area, 292 sq.mi.
09030009 -- Lake of the Woods. Minnesota. Area, 1220 sq.mi.

Figure 10. Aerial photograph of the Souris River near Sherwood (Photograph Credit, US Geological Survey).

Figure 11. Aerial photograph of the Souris River near Foxholm (Photograph Credit, US Geological Survey).

Figure 12. Aerial photograph of the Souris River near Minot (Photograph Credit, US Geological Survey).

Figure 13. Souris River above Minot (Photograph Credit, US Geological Survey).

Figure 14. Aerial photograph of the Souris River near Verendrye (Photograph Credit, US Geological Survey).

Figure 15. Aerial photograph of the Souris River near Bantry (Photograph Credit, US Geological Survey).

Figure 16. Souris River near Bantry (Photograph Credit, US Geological Survey).

Figure 17. Aerial photograph of the Souris River near Westhope (Photograph Credit: US Geological Survey).

issue that, in part, contributed to formation of the Souris River Bilateral Water Quality Monitoring Group in 1989 (http://www.mb.ec.gc.ca/water/fa00s05.en.html last accessed May 1, 2007). Water quality in the Souris River and its tributaries is frequently marginal, particularly for some communities in the basin that display exceedances of secondary water quality standards. Within a landscape setting, soil erosion of agricultural lands is also linked to diminished water quality, particularly at Lake Metigoshe, George Lake, Buffalo Lodge Lake, and Balta Dam. In riparian areas of the Souris River and its tributaries, river channel obstructions and streambank erosion also occur.

Residuals from Proposed Treatment Alternatives. Three of the four alternatives proposed for treatment of source waters from Lake Sakakawea include processes which will generate residuals. These treatment derivatives occur as sludge or potentially biosolids that will require management for their disposal and will inevitably present some level of risk to the environment as a consequence of water source management practices in the NAWS service area.

Sludge and (potentially) biosolids that are derivatives of the source water treatment process are briefly considered in this analysis, since the type of treatment process will influence the characteristics of these materials. Hence, their risks may differ from one treatment regimen to another. A focused analysis of risks associated with treatment residuals should be deferred until alternatives of choice have been winnowed and more detailed engineering designs are available for those selected for further consideration.

In general, water treatment residuals are those solids that are separated from source waters during the treatment process. Under the auspices of the Safe Drinking Water Act (SDWA), Clean Water Act (CWA), and other environmental laws and regulations, EPA and the states have developed standards for management of sludge generated during the water treatment process. Water treatment facilities, including some of those proposed for the NAWS project, produce sludge during the initial phases of the water treatment processes such as flocculation and filtration. Sludge disposal in lagoons or drying beds commonly provides for an economical, short-term management practice, but the long-term disposal requires other management practices dependent on landfill operations or incineration. Disposal of sludges in landfills has become increasingly expensive and difficult to accomplish, however, because of limited available land for disposal as well as high tipping fees at landfills. Driven by increasing costs, beneficial use options have been proposed for these materials, which are then referred to as biosolids.

Treatment residuals may be managed in various ways, including the development of marketable residuals products or biosolids. Biosolids may be used to fertilize or condition the soil and may be processed as pellets, compost, and alkaline materials, depending on the targeted application. Beneficial use of residuals, e.g., as a fertilizer or soil conditioner is regulated under federal and state law and may require site-specific approvals, depending on the nature of the residual. Residuals may also be incinerated or managed in landfills, depending on the materials that comprise the sludge or biosolid materials. For applications where biosolids are released directly to the environment, concerns have been raised by regulators in regard to the chemical and biological characteristics of the materials and their potential risks to human and environment. To address this concern, drinking water sludge must be characterized in compliance with federal and state regulations. Thus, residuals of the water treatment processes envision for NAWS may be applied to land as a soil amendment in the form of biosolids, or disposed in a surface disposal site as sludges or derivatives of an incineration process. Depending on the regulatory drivers in play, state and federal standards will require a permit for disposal in order to ensure water treatment residuals are adequately managed, e.g., residuals management is regulated in part by the National Pollutant Discharge Elimination System (NPDES).

These initial steps in Problem Formulation helped bound the analysis by identifying Reclamation's resource management needs and specifying critical questions related to biota transfers linked to interbasin water transfers. In the next section, a nested conceptual model has been developed that guides the analysis of risks and the subsequent characterization of risks and attendant uncertainties, particularly as those relate to the biological consequences potentially realized if biota transfers occur.

2.3 NAWS Conceptual Model

The conceptual model developed for NAWS as an outcome of Problem Formulation was not unlike that developed for RRVWS (USGS 2005a,b), which had resulted from collaboration with Reclamation and stakeholders. For NAWS, the iterative process characteristic of the risk assessment process yielded nested conceptual models (Figure 18A-B) that reflected the regional context underlying the interbasin water diversion issues previously detailed in USGS (2005a,b, 2006). Figure 18A and Figure 18B spotlight biota treatment alternatives that are central to resource management issues associated with the project. As such, these models illustrate the interrelated ecological and engineering components that characterize the interbasin water transfer process captured in NAWS. The nested, operational conceptual model that guided this analysis incorporates sources for biota transfers from the Missouri River basin potentially emigrating to the receiving Souris River basin through various pathways, including those (1) directly reflecting interbasin water transfers linked to diversions from the Missouri River, (2) other invasions mediated by alternate routes of biota transfer dependent on human intervention (but not NAWS-related) pathways, or (3) invasions independent of anthropogenic activities.

Development of the conceptual model for NAWS reflected the collaborative process conducted earlier by Reclamation and stakeholders for the RRVWS project. The predicating conditions focused on biota transfer issues for RRVWS project, principally the pathways and engineering countermeasures intended to reduce biota transfer risks, were closely aligned with those concerns for the NAWS project. As such, these project-specific attributes influenced development of the conceptual model, particularly the biota of concern linked to waterborne disease agents and cyanobacteria. As a primary outcome of Problem Formulation, the conceptual model helped identify ecological receptors most likely impacted by exposure to biota potentially transferred to the Souris River basin from Missouri River source waters, and helped identify assessment endpoints potentially of concern when potential adverse effects associated with a biota transfer were considered within the context of risk characterization and a preliminary evaluation of consequences and uncertainties.

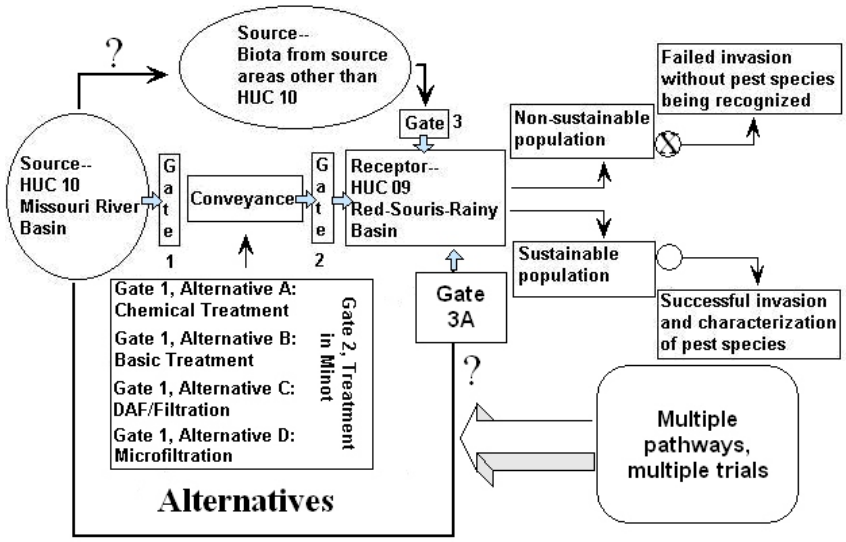
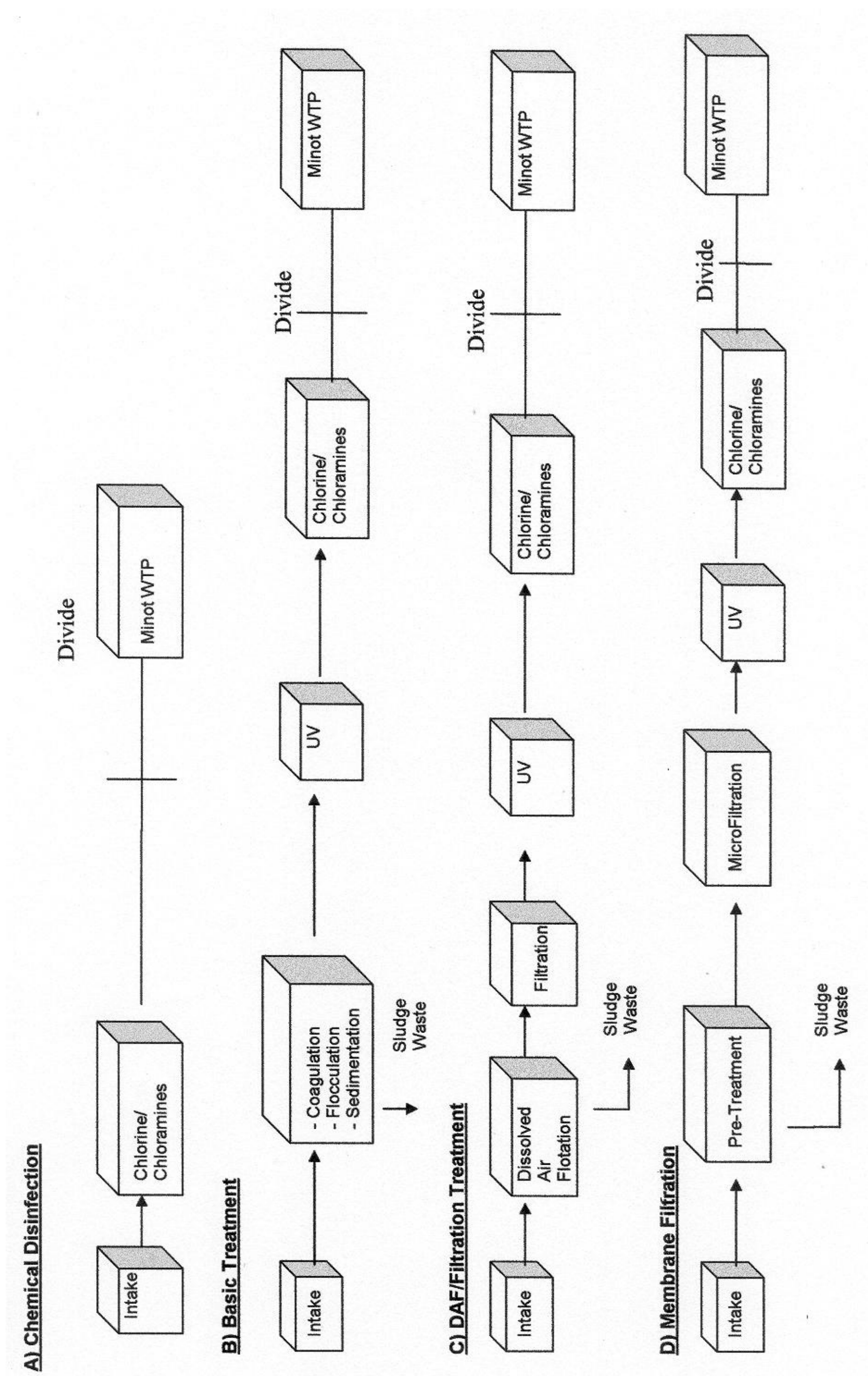


Figure 18A. Primary conceptual model linking sources and receiving areas via alternatives for moving water from the Missouri River to Souris River basin.

Figure 18B. As a nested subset of Figure 18A, the water treatment alternatives illustrated here become the focus of the risk reduction and preliminary failure analysis necessary to the evaluation of biota transfer risks.



2.4 Overview of Data-Mining and Analytical Tools

Risk analysis may be conducted with various levels of effort and tap into a variety of data and information available to the analyst. From a technical perspective, there are three varieties of risk analysis that potentially serve natural resource managers in their efforts to manage risks in the face of various levels of uncertainty (see ASTM 2004; EPA 2003, 1998, 1992; Foran and Ferenc 1999). While terminology varies from author to author, the analysis of risks can be implemented through (1) "desktop" efforts reliant on available information (e.g., open-source, peer-reviewed technical literature) and existing data sources, (2) screening efforts that are implemented along a spectrum of designed or observational studies, and (3) comprehensive efforts that are generally phased, interrelated studies resulting from previously completed desktop and screening level efforts. These categories may be conventionally characterized as discrete forms, and a desktop analysis may be implemented with various levels of effort, ranging from a preassessment activity that provides analysis and commentary sufficient to support decisions regarding the need for further study (e.g., NOAA 1997) to comprehensive studies that are variously implemented as data mining or integrated field-laboratory efforts involving designed studies to address environmental or engineering issues (see Downes et al. 2002; Doppelt et al. 1993; Margoluis and Salafsky 1998).

The current investigation is a focused desktop-level analysis that was designed to address questions reflected in the conceptual model that closed the preceding section. As a desktop analysis of risks, the current work was implemented through a comprehensive literature survey targeted on the list of biota of concern (Table 2) and the engineering alternatives being considered in the DEIS (Table 5), including failure-related data and engineering literature focused on components of the proposed control systems serving the water transfer process. The literature survey yielded existing information, largely peer-reviewed literature and data compilations (see USGS [2005a,b, 2006]) that was evaluated using available data analysis tools as briefly summarized here and in greater detail in USGS (2005a, 2006).

In the current investigation, a variety of methods have been applied to risk and failure analysis, particularly within the context of risk reduction and risk management. Although reliability theory developed independently from the mainstream of probability and statistics, its application to a range of engineering and natural resource management issues assures analysis commensurate with the available data. Although specific methods of choice are dependent on the amount and quality of data potentially available for the analysis, available guidance offers analytical options that are key to this initial characterization of likelihoods for system failure and its potential role in biota transfer (see, e.g., Tung et al. 2006, Pukite and Pukite 1998, Muhlbauer 2004, Kleiner et al. 2005, Grayman et al. 2001, Cromwell et al. 2002, Cesario 1995).

For example, the control systems envisioned for NAWS and considered in the DEIS (Reclamation 2007) to achieve an interbasin water diversion are “repairable systems” having a history that may serve the present analysis. The reliability of any system is the product of the reliability functions of the components, since “survival” of component parts is required for the system to survive. This building up to the system from the individual components was initially considered in terms consistent with the design specifications, e.g., specific types of water treatment such as pre-treatments followed by dissolved air flotation (DAF), UV treatment, or microfiltration and specification of system components throughout the transmission system. Such a "bottom-up" method can be subsequently refined, if specifications change and as greater specification is gained through the project's development, e.g., incorporation of a water distribution system as NAWS project develops through time.

As a first iteration, failure of a control system may be characterized by a "macro-rate constant" that reflects a composite of failure rates of non-repairable components of the system. If data are sufficient to higher resolution analysis, constituent failure rates may be characterized following a hazard analysis-critical control point (HACCP) process, so risk management practices may be developed to minimize risks potentially associated with biota transfer. Industry experience with failure rates will be used in the analysis, in part, as a characterization of baseline. Data harvested from earlier reports in a 3-report series (USGS 2005a,b, 2006) that considered biota transfer and water treatment-water transmission projects contributed to the analysis of biota transfer consequent to interbasin water diversions, particularly as that breach in "biological security" may be linked to control system failure. Depending on data available for analysis, repair rate models based on cumulative failures over time may be developed, again with HACCP guiding the analytical process. If data available to support this analysis are sufficient, then control systems may be identified that present advantages over competing alternatives. Yet, the paradox of reliability analysis based on historic data is, the more reliable a water treatment and water transmission system is, the more difficult to compile failure data for the analysis. Hence, censored data and the lack of failures may dominate existing data.

While a comprehensive review of the tools used in this failure analysis is not necessary to the management of risks, a brief background on the literature and data search completed to support this analysis follows, which is then extended in an overview of survival and reliability analysis as that relates to the current evaluation of control systems identified in the DEIS (Reclamation 2007). The failure analysis reported herein directly compliments the risk reduction and failure analysis summarized in USGS (2005b, 2006). For a more extensive treatment of any of the analytical tools discussed in this section, the reader is referred to references included in Section 6, as well as earlier reports in this series (USGS 2005a,b, 2006).

2.4.1 Literature Search and Collection of Existing Data and Information. Natural resource managers rely on a wide range of data sources to develop and implement management practices. The work summarized in this report reflects technical findings on questions related to biota transfers potentially resulting from water diversions from the Missouri River to the Souris River basin, issues similar to those previously considered in USGS (2005a,b, 2006). As a resource management tool, hazard and risk analysis have found increasing application for crafting adaptive resource management practices wherein technical inputs to a managed system (e.g., river, wildlife refuge, agriculture lands) are considered within a "what-if" context focused on potential outcomes that likely influence practices and policy proactively (see Gunderson et al. 1995; Holling 1978; Jensen and Bourgeron 2001; Walters 1986). Regardless of landscape setting, and whether it is solely spatial or spatiotemporal, an initial evaluation of risks involved in various management practices available to the manager may be solicited for guidance on which of many management practices might be applied to the specific circumstances. Often, a "desktop" risk analysis is the first step in the characterization of risks and the evaluation of and its dependence on existing data and information directly or indirectly linked to the questions identified in Problem Formulation.

For evaluating existing biology and ecological data and information related to interbasin water diversions envisioned for NAWS, a desktop analysis reliant on available data and existing information was completed; hence, the analytical tools applied were more observational than experimental and relied on data-mining search and compilation (see Chen 2001; Wolkenhauer 2001). As such, collection of data in desktop studies is similar to preliminary field investigations in ecological studies, since data in ecological and environmental studies, especially reconnaissance level efforts, rely on designed observational studies. The primary tool in data collection for desktop analysis is data mining, a discipline lying at the interface of statistics, database technology, pattern recognition, and machine learning. Data mining is focused on the secondary analysis of data extracted from the existing literature (e.g., previously published material, compiled databases) in order to characterize relationships among variables typical of new questions that may be linked to these existing sources of information. Data mining relies on an inductive process and is primarily concerned with secondary data analysis.

2.4.1.1 Literature Search for Biological and Ecological Data and Existing Literature. The main database providers for the current work included Cambridge Scientific Abstracts (CSA) and Online Computer Library Center (OCLC) FirstSearch. Databases searched in CSA included Aquatic Sciences and Fisheries Abstracts, Biological Sciences, Environmental Sciences and Pollution Management, and to a lesser extent, AquaLine, Water Resources Abstracts, GeoRef, Biology Digest, Conference Papers Index, Medline and Toxline. Databases in OCLC FirstSearch that were searched included Agricola, ArticleFirst, BasicBiosis, Dissertations, GeoBase, and WorldCat. BioAgIndex, Electronic Collections Online, PapersFirst, and Proceedings. Ingenta database provider was also used for some searches.

Search terms. The data search and acquisition was initially completed as part of earlier studies focused on interbasin water diversions proposed as part of the RRVWS project (see USGS 2005a,b, 2006), which provided high quality data on biota of concern identified for this work. Literature searches for high-priority biota of concern relied on scientific name (at genus or species level), and common names, if applicable. Depending on the number of citations found, additional search terms were added. Terms used would refer to the distribution and spread of the species, its life history and habitat, and its interaction with other species. In some cases, for example, the bacteria, the focus was on the natural occurrence of the biota and risk assessment. Citations related to detection and control measures were generally included. When there were an overwhelming number of citations, the search in some databases was limited to more recent references (within the last 10 years).

Search outcomes. Existing literature and data collected from the literature search were dominated by "effects data" derived from past studies (observational and experimental) focused on the effects that a particular biota of concern had on a receiving system or target organisms, and "pathways data" which reflected available literature resources focused on the spatiotemporal linkages between biota of concern and their geographic distributions. Graphically, Figure 19 through Figure 21 summarize citation counts for biota of concern and reflect a relatively wide range in literature and existing data available for the current data-mining effort focused on the biota transfer questions identified during Problem Formulation.

Figure 19. Count data for protozoa and myxozoa included as biota of concern for NAWS.

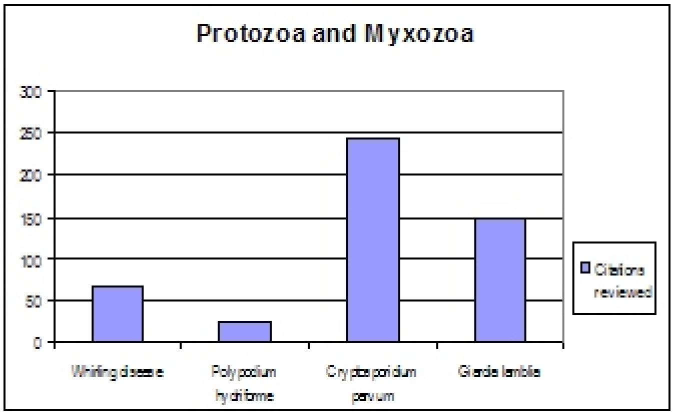


Figure 20. Count data for bacteria and viruses included as biota of concern for NAWS.

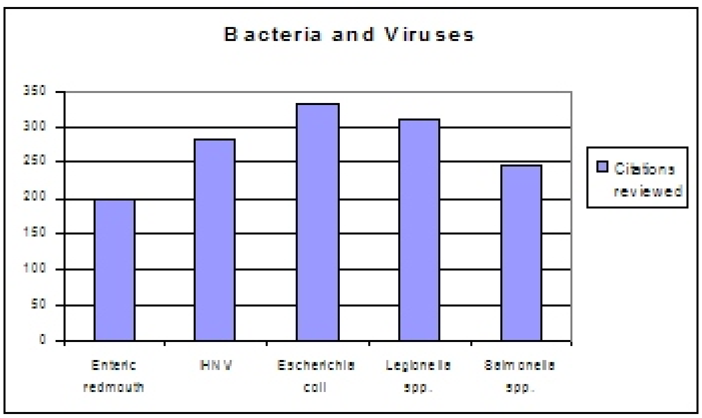
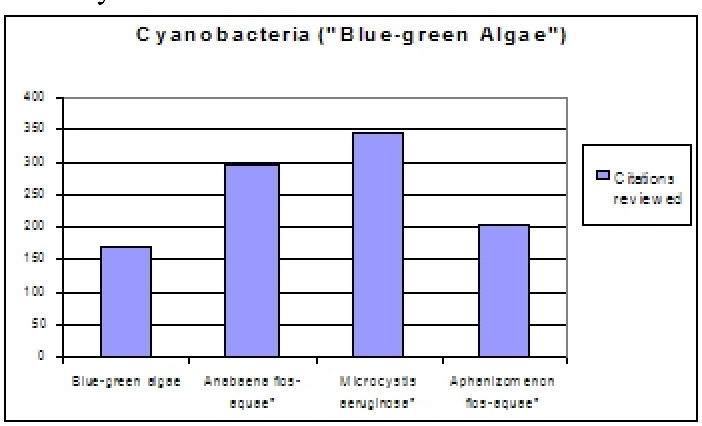


Figure 21. Count data for cyanobacteria included as biota of concern for NAWS.



2.4.1.2 Literature Search for Control System Failure Data and Existing Literature. As with the search focused on existing biological and ecological data and literature, existing failure rate data was available from a variety of sources as detailed in USGS (2006). For the literature search supporting the failure analysis, the main literature database providers included CSA and OCLC FirstSearch. Databases searched in CSA included Environmental Sciences and Pollution Management, Water Resources Abstracts, GeoRef, and Conference Papers Index. Databases in OCLC FirstSearch searched included Agricola, ArticleFirst, BasicBiosis, Dissertations, GeoBase, and WorldCat. BioAgIndex, Electronic Collections Online, PapersFirst, and Proceedings. Ingenta database provider was also used for some searches. Focused database searches of American Society of Civil Engineers (ASCE), American Society of Mechanical Engineers (ASME), and National Research Council Canada-Institute for Research in Construction (http://irc.nrc-cnrc.gc.ca/index_e.html) libraries provided data sources for analysis of water system infrastructure and its components.

Search terms. Beyond data available through compilations from government and industry sources, searches for failure data for the conceptual designs advanced in the DEIS (Reclamation 2007) for the biota treatment and water transmission system tapped data sources available through American Water Works Association (AWWA), ASCE, and ASME. In addition to professional associations such as these, collaborative government-industry sources (e.g., joint EPA-AWWA publications) were tapped to acquire quality data that characterized, e.g., failure rates for water treatment processes such as UV disinfection and microfiltration, mechanical failure rates for pumps, valves, and gates, and pipe (such as ductile iron pipe, or DIP). Depending on the quantity of citations or data compilations discovered, reiterated searches were completed using search terms to discriminate among available data sources, e.g., distinguish between failure rates for different types of pipelines.

Search outcomes. Existing literature and data collected from the literature search reflected both observational and experimental data, with much of the observational data acquired consequent to field studies focused on water distribution systems and evaluations of these system's reliability. Please refer to USGS (2006) for tabular summaries of control-system component failure histories, including available data on failure rates and generalized analysis of system failures potentially linked to biota transfer events.

2.4.2 Analytical Tools for the Analysis and Characterization of Risks. A complete synopsis of tools applied to the analysis completed in this study is reported in USGS (2005a,b, 2006), with particular attention called to USGS (2005a), Appendix 4 and USGS (2006) for tools applied for risk and failure analysis, respectively.

3.0 Evaluating risks and biological consequences of biota transfers potentially associated with control system failure

USGS (2005b, 2006) had earlier completed a preliminary analysis of alternative technologies identified to reduce risks associated with biota transfers directly linked to interbasin water diversions. Given the similarities in the initial conceptual designs for NAWS control systems (Reclamation 2007), this analysis parallels that previously completed for RRVWS project (USGS 2005a,b, 2006).

As noted in USGS (2005a,b, 2006), analysis of risks linked to control system failure should be fundamental to anticipating and minimizing risks and consequences of biota transfers potentially associated with interbasin water diversions between Missouri River and Hudson Bay basins (for NAWS, the Souris River subbasin within the Hudson Bay watershed). As such, an analysis of risks associated with failure of controls systems—conveyance and water treatment—reflects a preliminary evaluation of system reliability, given the critical function that the control system plays in assuring that biota transfers are not realized in the process of water diversion. System failure could result in biota transfer and potentially the establishment of invasive species or shifts in metapopulations of, e.g., disease agents cosmopolitan in their distribution across the northern Great Plains and Great Lakes basin. This baseline risk and failure analysis could support a HACCP process previously identified as a risk management tool commonly applied across a range of industrial and resource management issues, including the prevention and control of invasive species (see USGS 2005a,b, see also http://www.haccp-nrm.org/default.asp, FAO/WHO 1998, WHO 1997). Water treatment and transmission systems should be scalable and designed with sufficient flexibility to anticipate future needs that are currently unknown or poorly characterized. Given continuing advances in water treatment—including applications of “old tools” responsive to contemporary concerns—and the ever-changing technical views on “best practices” for water treatment, designed flexibility is necessary.

Analysis and characterization of risks focused on conveyance and treatment, and was based largely on methods applied to similar analysis for RRVWS project (USGS 2005a,b, 2006). The reader may also refer to Aven (2003), Barlow (1998), Blischke and Parbhakar Murthy (2000), Borgelt and Kruse (2002), Huzurbazar (2005), and Appendix 4 in USGS (2005a) derived in part from NIST/SEMATECH (2004; http://www.itl.nist.gov/div898/handbook/) for additional background information for data analysis.

3.1 Conveyance risk

Conveyance risk is common across all the alternatives currently identified in the NAWS DEIS (Reclamation 2007). Hence, a single risk analysis and characterization is sufficient to this iteration of the evaluation of NAWS alternatives. Future iterations of this analysis may be warranted, because subsequent engineering designs predicated on an alternative of choice may yield resolution sufficient to more detailed analysis focused on risks potentially associated with different treatment-conveyance dependencies. The reader is referred to USGS (Appendix 4 of 2005a,b, 2006) for background on analytical tools applied to this analysis of risks and a preliminary evaluation of risk reduction potentially associated with alternatives being considered in DEIS currently being prepared for NAWS.

For the current analysis of risks associated with conveyance, NAWS presents a relatively simple infrastructure when compared to control systems considered in USGS (2005b, 2006). As noted in Section 2, the water transmission pipeline connecting source waters withdrawn from Lake Sakakawea with Minot WTP is nearly complete, covering the nearly 45 mile interval between source and terminus via a corridor closely aligned with the Highway 83 (see Figures 3 through 5). And, in contrast to alternatives posited for RRVWS water transmission pipelines, pipe diameters reflected in the conceptual designs for NAWS are relatively invariant (depending on their location in the water transmission system, pipe with be either 30 inches or 36 inches in diameter). Hence, fluid flows within the transmission pipeline will be relatively uncomplicated, and failure risks associated with dynamic changes linked to pipeline configuration should be relatively limited between the point of withdrawal on Lake Sakakawea and the transmission pipeline's terminus at the Minot WTP. Overall, the water transmission pipeline has relatively linear attributes and has a limited number of isolation valves in those segments occurring along the greatest elevation change between Lake Sakakawea (historic elevation varies annually and seasonally between 1807 and 1855 feet Mean Sea Level [MSL]) and the prairies lying to the north where maximum elevations of approximately 2240 feet MSL occurring along pipeline route between Max (elevation, approximately 2093 feet MSL) and Minot (elevation, approximately 1716 feet MSL; see Table 4). Blow off valves are located as needed throughout the course of the pipeline, and once a treatment alternative has been selected, a booster pump station will be constructed near the proposed water reservoir near Max, North Dakota.

Given the (1) the pipeline's presence in each of the alternatives advanced in the DEIS (Reclamation 2007), (2) the relatively simple pipeline configuration anticipated for the NAWS water transmission pipeline, (3) the use of DIP in its construction, and (4) the existing failure history of DIP in water transmission pipelines (see USGS 2006), risks associated with failure in the conveyance component of the control system designed to deliver water to Minot for potential distribution to communities in the Northwest service area are not useful in discriminating among NAWS alternatives. Reliance on the common pipeline feature in each conceptual design contributes nearly identical component risks to an analysis of potential risk reduction. However, if subsequent control system designs warrant and data are sufficient, reiteration of the analysis focused on conveyance may be indicated, particularly if dependencies between treatment operations and conveyance operations exist and provide means for discriminating among alternatives.

3.2 Water treatment control systems as risk reduction tools

Various control technologies have been developed to assure that water disinfection is achieved, and exposure to drinking water as a major factor in disease outbreaks and epidemics has been reduced over the past 75 to 100 years. These control technologies range from chemical and physicochemical treatments (e.g., chlorination and chloramination, UV disinfection) to physical barriers acting as filters (e.g., pressure-driven membrane technologies), each capable of reducing risks of biota transfers associated with interbasin water diversions (see Letterman 1999). These technologies may be used singly or in combination in control systems designed to meet user specifications, yet regardless of configuration, the systems themselves present collateral risks that must be considered in any water resource management plan, e.g., chemical treatments such as chlorination may yield unintended byproducts which may pose risks consequent to interaction with naturally-occurring materials in the water (see, e.g., Percival et al 2004, Letterman 1999).

3.2.1 Coagulation-Flocculation-Sedimentation. These pre-treatment steps are typical of water treatment facilities, including an initial physical screening of source waters wherein physical debris (e.g., leaves, logs, sticks, litter such as plastic bottles), large invertebrates and fishes are removed from intake water drawn into the treatment plant. Following removal of physical debris and larger biota, intake water headed to treatment facilities will pass through a series of conventional chemical treatments—coagulation-flocculation-sedimentation—intended to remove suspended solids, some dissolved chemical substances (e.g., iron, calcium, magnesium), and some impurities from raw waters. These three conventional pre-treatment steps reduce or remove suspended and dissolved solids which improves the appearance and taste of drinking water, and reduce or remove some of the chemical and microbiological contaminants that might be harmful to receptors (e.g., humans, wildlife, and fishes). The intended outcomes of pre-treatment are enhanced system performance, e.g., in systems relying on UV disinfection, reducing TSS and and hardness benefit water treatment. Depending on the engineering design, a "presedimentation" step may be included to remove settleable solids present in the water by gravity prior to conventional chemical treatment.

Once intake water has passed through conventional treatment, various options are available to engineering design, including filtration, disinfection, and water softening. Filtration options range widely (e.g., media filtration, often times sand or other granular materials through membrane filters of various porosities), but all target removal solids and fine particles of various sizes, depending on the system's design. Disinfection options vary, depending on product water's specified end-use. In general, the disinfection process inactivates waterborne pathogens to assure safe consumption, e.g., for human populations, domestic animals, or application to other water uses (e.g., industrial applications, agriculture). Although not indicated in all water uses, water softening may also be incorporated into a system's design in order to remove minerals (primarily calcium and magnesium) that contribute to water hardness.

3.2.2 Chemical treatments: Chlorination and Chloramination.[5] Disinfection in water treatment is required by the Surface Water Treatment Rule of 1990 and subsequent regulations (see, e.g., http://www.epa.gov/OGWDW/mdbp/ieswtr.html last accessed May 21, 2007) which mandates effective disinfection through (1) filtration pre-treatment of source waters followed by (2) inactivation of organisms such as bacteria and viruses through disinfection with, e.g., chlorination and chloramination, and (3) as applicable, treatment requirements for waterborne pathogens, e.g., *Cryptosporidium* spp. in addition to meet existing requirements for *G. lamblia* and viruses.

Water disinfection generally occurs as a two-step process wherein (1) particulate matter is removed by conventional filtration to reduce turbidity in source waters and thus, reduce

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[5]See USGS (2005) for expanded discussion of chlorine, chloramine, and chlorine dioxide disinfection and technical references supporting that discussion.

"habitat" for viruses and bacteria adsorbed to particulate material, and then (2) pathogenic microorganisms are inactivated by chemical treatments (such as chlorination and chloramination), physicochemical treatments (such as UV disinfection), or removed through physical treatments (such as membrane filtration; see, e.g., Letterman 1999 for overview of water treatment process; see also Mallevialle et al 1996, Duranceau 2001, Schippers et al 2004 for discussions of pressure-driven membrane systems). More often than not, combined water treatment technologies are applied to the water disinfection process.

Chlorination has been used as an agent for disinfection in the US over the past 100 years (see USGS 2005a; see also Letterman 1999, and http://www.awwa.org/Advocacy/learn/info/HistoryofDrinkingWater.cfm last accessed May 21, 2007). Much of the process of chlorination relies on technology developed in the 1950's and 1960's (see White 1999 and earlier editions of this reference). Although the tools for chlorination have continued to be refined, few innovations have been made recently. Other disinfection technologies have been developed (e.g., ozonation, UV irradiation), but chlorine remains widely used as a disinfectant throughout the US because of its low cost, ability to form a residual, and its effectiveness at low concentrations. Overall, chlorine presents numerous advantages for disinfection, including the chemical's ease of application and residual presence in the distribution system, its effectiveness at low concentrations, and its relatively simple conversion to chloramines which also provide strong residual effects with limited formation of disinfection by-products (DBPs). From an engineering cost perspective, chlorine is a relatively inexpensive disinfecting agent.

Despite these advantages, chlorine has "down side" risks that must be managed, if it is selected as a disinfection agent of choice. Chlorine reacts with organic materials in source waters, effectively reducing its concentration while creating trihalomethanes (THMs) and other DBPs compounds that may become health risks in drinking water distribution systems. More importantly from the perspective of its role as a disinfection chemical, chlorine provides poor disinfection for *Cryptosporidium* spp. and other microorganisms characterized by chlorine-resistant stages in their life history (e.g., spore formation; see USGS 2005, Appendix 3B). For target organisms such as *Cryptosporidium* spp., filtration provides an alternative disinfection method used singly or in conjunction with chlorination (see, e.g., Schippers et al 2004, Duranceau 2001, Mallevialle et al 1996).

Treatment with chloramine. Chloramines are the product of chloride reacting with ammonia, and some chloramines, particularly monochloramine, have also been used as disinfectants since the 1930's. Chloramine use in drinking water disinfections is an increasingly common standard practice among water utilities (see Haas 1999), in part, because of chlorine's disadvantages as a disinfectant. While chloramine is a weaker disinfectant than chlorine, it is more stable in water solutions under operating pH and the chemical's benefits as a disinfectant are available over longer periods of a system's operation.

Chloramine is use in water treatment primarily as a secondary disinfectant, since it helps maintain a disinfectant residual in the distribution system. Chloramine is also not as reactive as chlorine with organic material in water, thereby producing substantially lower concentrations of DBPs such as THMs and haloacetic acids (HAAs) which have associated adverse health effects at high levels. Because the chloramine residual is more stable and longer lasting than free chlorine, it provides better protection against bacterial regrowth in systems with large storage tanks and dead-end water mains, and it effectively controls formation of biofilms within the distribution system. Controlling biofilms reduces microbial habitat in distribution systems, which reduces concentrations of coliforms and other microorganisms, and helps reduce biofilm-induced corrosion of pipes and habitat amenable to colonization of pathogens or their hosts. In addition to these technical advantages of chloramine, many drinking water utilities in the US have switched to chloramine as their disinfectant residual, since regulatory limits for THMs in drinking water have been lowered with promulgation of the Stage I Disinfection Byproducts Rule and subsequent administrative targets for lowering standards of DBPs (see EPA 2001a for a quick reference, or EPA 2001b).

3.2.3 Dissolved Air Flotation: An Alternative Treatment Process to Reduce Risks Potentially Associated with Interbasin Biota Transfers. In the current analysis, concern about biota transfer issues encouraged consideration of other control measures, including those being applied to invasive species management that have been incorporated in engineering designs considered by Reclamation as their NEPA compliance effort continues. Dissolved air flotation (DAF) is currently one tool being used in management of invasive species, e.g., in reducing risks of unintended biota transfers that might manifest themselves as species invasions consequent to ballast water exchanges in near-shore environments. DAF may be equally amenable to incorporation into control systems fully designed to address interbasin biota transfer issues, once alternatives of choice have been identified.

Uncontrolled releases of ballast water have become significant transport mechanisms for introduction of nonindigenous species to surface waters throughout the world (Barrett-O'Leary 1998; Carlton 1985), and reflect technical issues similar to those initially motivating concerns of biota transfers considered in USGS (2005a). As noted in USGS (2005a), species capable of successfully emigrating from Missouri River basin to Red River and Souris River basins have life history attributes similar to species transferred in ballast water, where they survive suspended in ballast water or in sediment deposits of ballast tanks.

Various ballast-water management strategies have been applied to control invasive species, including a range of physical, chemical and biological treatment techniques. One technology identified as an engineered unit operation for separation of nonindigenous species in ballast water is DAF, a risk reduction tool potentially amenable to preventing potential biota transfers associated with interbasin water diversions. DAF has a long history in water treatment (Kiuru and Vahala 2001, Tchobanoglous et al. 2003), and has become a proven technology in the wastewater treatment industry for particulate separation.

DAF overview. Simply stated, DAF is a physical process, most often designed as an integrated unit operation intended to follow source water pre-treatment, e.g., conventional sediment-coagulation-flocculation and pH adjustment. DAF unit operations vary in their configuration with water treatment systems, and in general serve as a water clarification process that removes suspended solids from water, while minimizing use of bulk chemicals in the treatment process. In brief, DAF relies on the injection of microscopic air bubbles into a feed-water stream, which causes particles to float on the surface of a basin with inclined settling plates. These particles are continuously skimmed off and removed with a wastewater stream, and is particularly useful when treating waters high in total suspended solids (TSS) or having highly variable suspended solids content. DAF is effective in removing suspended solids in the initial treatment of river and other surface waters prior to demineralization, membrane filtration and reverse osmosis (RO) and other water purification processes. Water treatment systems incorporating DAF into their design provide engineering advantages, e.g., costs reduced relative to unit operations conforming to performance criteria that exceed conventional flotation technologies. Beyond initial costs for design and construction, DAF reduces chemical costs and increases performance criteria when incorporated into routine operations and maintenance (O&M) programs (Kiuru and Vahala 2001, Tchobanoglous et al. 2003).

In contrast to a settling process, flotation is a solids-liquid or liquid-liquid separation that results when low-density particles occur in a liquid of higher density. In general, three types of flotation have been characterized: natural, aided, and induced flotation. Natural flotation is simply a process occurring when differences in density are naturally sufficient for separation, e.g., settling or sedimentation processes. In contrast, aided flotation occurs when external forces promote the separation of particles that are naturally floatable. Induced flotation occurs when the density of particles is artificially decreased to allow particles to float, and is a process that depends on the capacity for certain solid and liquid particles to link up with gas (usually air) bubbles to form "particle-gas" with a density lower than the liquid. Mechanical flotation is a general term to identify a process relying on dispersed air to produce bubbles measuring from 0.2 to 2 mm in diameter, while DAF is a form of induced flotation that relies on very fine air bubbles ("microbubbles," 40 to 70 microns).

DAF processing downstream from a conventional sedimentation-flocculation-coagulation process removes solids by attaching "microbubbles" to the floc, subsequently floating solids to the surface where they are skimmed by mechanical or hydraulic means as process residuals (biosolids). Organic and inorganic chemicals or other constituents entrapped in the solids-microbubble complex (such as algae, *Cryptosporidium* spp., and *Giardia* spp.) are generally reduced in concentration in the effluents leaving a DAF unit operation. A DAF pre-treatment will likely reduce membrane fouling in water treatment systems using membrane technologies. Many factors influence any flotation process, including air hold-up; bubble-size distribution and carryover; degree of agitation; residence time of bubbles in source waters; solids content, particle size and gravity; shape of particle; processing of the floated product; hydration of the solid surface; and flotation reagents (see USGS 2005b, 2006, Kiuru and Vahala 2001, Tchobanoglous et al. 2003).

In the past 30 years, DAF has been successfully applied to waste treatment to remove suspended solids, grease, oil and biological solids from wastewater, and in the past 10 years has been applied to management of invasive species. DAF can be effective for removal of particulates, including algal cells, and oöcysts of *Cryptosporidium* and other resistant life stages of disease agents. As proposed in Alternative C, DAF is applied to the biota treatment process in conjunction with media filtration (see Letterman 1999, AWWA/ASCE 1998; see also http://www.agr.gc.ca/pfra/flash/filtration/ en/filtrationtxt_e.htm last accessed July 11, 2007).

Media filtration. Media filtration involves a solid substrate such as silica sand, anthracite, crushed granite or other material (such as granular activated carbon) to filter water for drinking, aquaculture, irrigation, and other applications such as treatment of waste water or storm water. Granular bed filtration is often used in series with a precoat filtration operation that uses diatomaceous earth or perlite as a filter medium (Letterman 1999). Performance of media-filtration unit operations depends on the size, shape, density, and hardness of the materials used in the unit operation, as well as the porosity of the media once the unit operation is configured and built. Filter performance is dependent on the design and operation of the filter, physicochemical pretreatment, and the efficiency of the cleaning of the media between filter runs, an operation generally accomplished by backwashing. Once performance criteria are specified, granular media filtration will remove particulates present in source waters and those generated during the preceding operations in the treatment process.

Granular media filtration is widely used in drinking-water treatment, given its capacity to remove microbes through a combination of physical–hydrodynamic properties and surface and solution chemistry. Independent of its proposed application in Alternative C, a range of materials may be removed from the input stream feeding a granular media filtration unit operation, including clay and silt particles, microorganisms such as bacteria, viruses, and protozoan cysts, colloidal and precipitated humic substances and other natural organic particulates, calcium carbonate and magnesium hydroxide precipitates resulting from lime softening, and iron and manganese precipitates. For example, slow sand filtration works through a combination of biological and physical–chemical interactions, with the biological layer of the filter (schmutzdecke) being effective for removal of microbial pathogens. Depending on intended post-treatment water use, chemical treatment may be required to attain specified performance criteria. Under optimal conditions, the combination of coagulation, flocculation, sedimentation and granular media filtration can result in 4-log or better removal of protozoan pathogens.

In contrast to granular bed filtration, membrane filtration removes microbial pathogens primarily by size exclusion (without the need for coagulation), and is effective in removing microbes larger than the membrane pore size.

3.2.4 Membrane filtration.[6] Membrane filtration technology has been increasingly applied to water treatment problems. The range of membrane technologies that have become efficient and safe water treatment alternatives are numerous (see Mallevialle et al. 1996; Duranceau 2001). Water treatment systems singly dependent on membrane filtration, or incorporating membrane technology within a multiple-treatment process, yield product waters of consistent quality that meets or exceeds water quality standards, especially with respect to disinfection (see, e.g., Schippers et al 2004). Membrane separation technology removes substances largely based on size and shape, with pore size and particle-size exclusion typically measured in nanometers (nm, or 10^{-9} meters), Angstroms (Å, or 10^{-10} meters), or molecular weight (MW, often times expressed as units, D for Daltons). A range of membranes have been developed with mass transfer

[6]See USGS (2005) for expanded discussion of membrane filtration and technical references supporting that discussion

properties and pore sizes such that ionic, molecular and organic substances measuring 1-1000 Å (MW between 100 and 500,000) are removed or rejected. As a "stand-alone" water treatment technology, membrane filtration is a physical process that may require little or no chemical treatment, depending on the choice of membrane device selected. Three general types are briefly considered: microfiltration, ultrafiltration, and nanofiltration (Figure 22; graphic after AWWA).

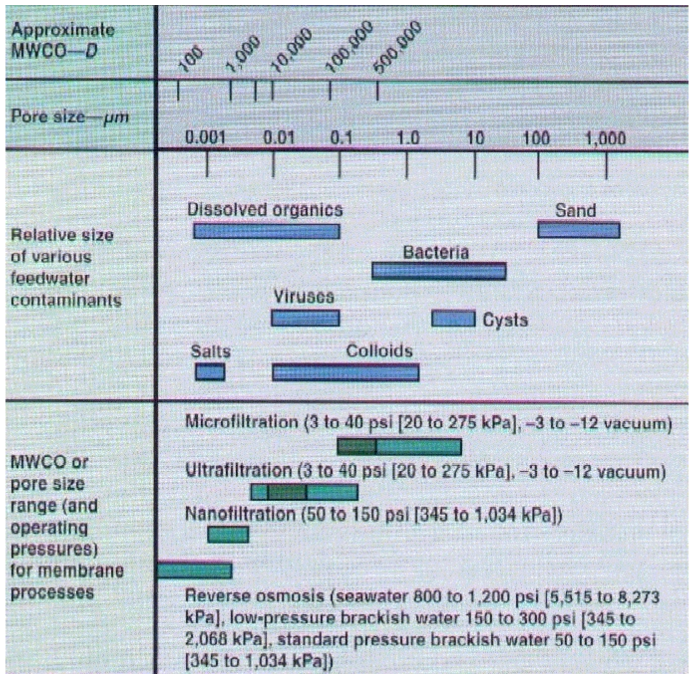

Figure 22. Molecular weight cut off (MWCO in Daltons [D]) values for range of filtration technologies currently available for water treatment (Source: American Water Works Association [AWWA]).

Microfiltration is characterized as a solid-liquid separation process with a molecular weight cut off between between 0.1 μm and 10 μm (Figure 22). Microfiltration reduces the passage of suspended particles, high-molecular weight lipids and fats, macromolecules, bacteria and protozoa (although *Cryptosporidium* spp. and *Giardia* spp. or their cysts may not be removed completely). It is frequently used for the production of drinking water and waste water treatment.

Ultrafiltration allows for filtration of smaller particles than microfiltration with a molecular weight cut off between between 0.01 μm (micrometers, 10^{-6} meters) and 0.1 μm, which effectively excludes all protozoa, bacteria and virus particles, as well as most proteins and high molecular weight organic compounds (Figure 22). Ultrafiltration is finding widespread use for a variety of applications such as producing drinking water, treating waste water and treating process water (e.g., discharges from agricultural, biotechnology, petrochemical, municipal waste streams).

Nanofiltration provides the greatest filtration capacity of the membrane technologies, with pore sizes less than 10 nm (Figure 22). As such, nanofiltration not only excludes those constituents separated by ultrafiltration, but also limits passage of divalent ions, dissolved organic material and sugars. Given the membranes characteristic molecular-weight cut off, nanofiltration provides for partial demineralization, which tends to yield potable water from slightly brackish water or humic-stained surface water(see Mallevialle 1996, Duranceau 2001).

3.2.5 UV Disinfection of Drinking Water.[7] Given the water treatment technologies proposed as part of the alternatives for NAWS control system, and in view of the "Best Available Technologies" being considered as part of regulatory guidance, UV disinfection technologies are briefly considered for NAWS as was previously done for RRVWS project (see USGS 2005a,b, 2006; see also Percival et al 2004; Mackay et al. 2001; Malley et al. 2004; Snicer et al. 2000).

UV technologies have long been known to be effective for viruses and bacteria in drinking water and guidelines for the disinfection of viruses have been published (e.g., Alternative Disinfectants and Oxidants Guidance Manual, EPA 1999). However until relatively recently, UV was widely considered to be ineffective for encysted protozoa, since cyst membranes were thought relatively resistant to UV irradiation. Given *Giardia* cysts served as a "standard" for chlorine dose determinations, no reductions in chlorine usage were gained by using UV prior to 1998 in view of the technical literature available at the time. Hence, UV disinfection was not widely used for surface waters in the US and Canada. However, over the past 8 to 10 years studies focused on UV disinfection have demonstrated its effectiveness for inactivating *Cryptosporidium* and *Giardia* at low to medium UV "doses" (see, e.g., Clancy et al 1998, 2000; Marshall et al 2003). In advance of new guidance and supporting technical support manuals for UV disinfection from EPA, water resource management agencies have begun to consider UV disinfection as an alternative for protozoa disinfection or to gain disinfection credits for UV for *Giardia*, so chlorine doses can be lowered to meet DBP standards.

Use of ultraviolet (UV) light to disinfect water of waterborne pathogens relies on the germicidal properties of a narrow range of the UV spectrum (Figure 23). In sunlight, UV spectrum consists of discrete bands, with UVA and UVB (280–400nm) reaching earth's surface, while much of the UVC is filtered by interactions with ozone in the upper atmosphere. Shorter wavelength, higher energy UVC penetrates cells and causes DNA damage. As a disinfectant for water treatment, UV is germicidal, provided "dose" is sufficient (e.g., exposure duration long enough to yield target disinfection). UV wavelengths ranging from 240 to 280 nanometers (nm) deactivate microorganisms by damaging their DNA. If not killed and DNA repair is not completed, UV-exposed microorganisms do not replicate and thrive (see, e.g., McKey et al 2001, Jacangelo et al 2002).

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[7]Elaborated from USGS (2005a,b) and references cited therein.

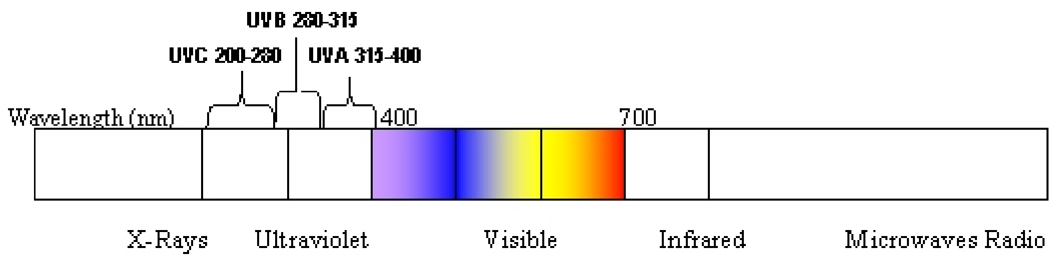


Figure 23. Electromagnetic spectrum illustrating ultraviolet (UV) relative to other forms of radiation.

UV dose measured in microwatt-seconds per square centimeter[8] is the product of UV intensity and exposure time. For disinfection targeted on *Giardia* spp., *Cryptosporidium* spp., and other large cysts and parasites, UV doses range from approximately 60,000-80,000 $\mu W\text{-}s/cm^2$ (see, e.g., McKey et al 2001, Jacangelo et al 2002). Most UV disinfection systems use low-pressure or medium-pressure mercury vapor lamps and expose water to UV by pumping the water around a sleeve within which the UV lamp is supported. UV systems can also be coupled with a pre-filter to remove larger organisms that would otherwise pass through the UV system unaffected. The pre-filter also clarifies the water to improve light transmittance; therefore, UV dose is achieved throughout the entire column of water. Proper handling and storage of UV-treated waters are a critical part of any UV treatment system, since UV treatment alone offers no residual disinfection. If bacteria are not killed as a result of UV exposure, organisms may undergo DNA repair (see, e.g., Mara and Horan 2003). The maximum absorption of DNA and maximum formation of photoproducts occurs between 260-265 nm. Unlike chlorination, UV treatment produces no known disinfection byproducts.

Water quality influences the effectiveness of UV disinfection, especially iron, water hardness, and total suspended solids (TSS). Performance of UV disinfection systems is optimal when iron concentration, hardness, and TSS are low, and UV fluence is high. Fluence is the product of light intensity and exposure time as milliJoules per square centimeter (mJ/cm^2), and is analogous to chlorine dose in water treatment jargon. To assure optimal performance, pre-treatment of incoming source waters may be required, including filtration, e.g., through a 5-micrometer filter, to reduce or remove iron and water hardness, as well as remove sediment which potentially provides habitat for microorganisms.

[8]Power is measured in Watts, and Joules are units of energy. To convert Watts to Joules, 1 Watt = 1 Joule per second of power or 1 Watt-second = 1 Joule.

3.3 Preliminary Evaluation of Risk Reduction Captured by Alternatives: Potential Risks Associated with Control System Failure and Their Root Causes

Regardless of the engineered system being evaluated, primary causes of system failure may be categorized as being linked to human factors, design or materials failures, extreme conditions or environments, and most commonly and importantly, combinations of these reasons. In evaluating natural hazards and failures of natural systems through time, analogous factors may be characterized, most of which are subject to age-related changes in the system or more aptly stated, age-related changes in system components. This failure analysis primarily focuses on water treatment and water transmission systems. The water transmission pipeline is a common feature shared by each alternative and is not a discriminating factor is differentiating risks given the system's specification at this time. Potential interaction between engineered control systems and natural resources will be considered primarily as part of the uncertainty analysis that accompanies this preliminary evaluation of risks and analysis control system failure.

For evaluating risk reduction potential captured in the DEIS for NAWS (Reclamation 2007), two general attributes of a risk reduction evaluation guided this preliminary analysis—the spatial attribute, or "where source water will be gained" to address water needs in the Souris River basin, and the implementation attribute, or "how the water will be delivered" to the Souris River basin. Given the predicating conditions for NAWS, the current analysis is simplified, since each of the four alternatives relies on the same source waters from Lake Sakakawea and share a common transmission pipeline in their design.

Alternative A serves as the "No-Action Alternative" required under National Environmental Policy Act (NEPA) of 1969 as amended ([Pub. L. 91-190, 42 U.S.C. 4321-4347, January 1, 1970, as amended by Pub. L. 94-52, July 3, 1975, Pub. L. 94-83, August 9, 1975, and Pub. L. 97-258, §4(b), Sept. 13, 1982)] 40 CFR Section 1502.14(d)), and provides a point of reference for evaluating action alternatives posited in the evaluation. Brief summaries of each alternative have been included in Section 2, and in the current section, categorical analysis was completed to address each alternative's risk reduction potential to discriminate among alternatives.

For this iteration focused on risks linked to water treatment regimens advanced in the DEIS (Reclamation 2007), risk reduction credits were assigned to each compartment within the proposed treatment operations. Rank scores reflected assigned values for ordinal data, with assigned values being simple binary scores or categorical rank-scores weighted so increasing value captured greater reduction in risks, e.g., 0 was assigned to alternatives lacking water treatment in the source area basin and 1 was assigned to alternatives having proposed water treatment near the Lake Sakakawea source in the Missouri River basin as indicated. Table 7 summarizes the initial evaluation of "risk reduction credits" that are associated with each of the alternatives. For this analysis the control system was considered in a categorical analysis of discrete compartments within a given treatment operation (see Appendix 4 in USGS 2005a) wherein alternatives were scored for, e.g., regimen for type of treatment process, extent of pre-treatment and disinfection, and release to the terminus.

Table 7. Summary of initial evaluation of risk reduction credits earned by each of the four alternatives being considered in the DEIS (Reclamation 2007).

Alternative	Step 1	Step 2	Step 3	Step 4	Within-basin		Step 5*	Total Rank Score
A	Chlorination-Chloramination					Continental Divide	Minot WTP	
Rank	1				1		2	3
B	Coagulation-Flocculation-Sedimentation	UV	Chlorination-Chloramination				Minot WTP	
Rank	1	1	1		3		1	4
C	Dissolved Air Flotation	Media Filtration**	UV	Chlorination-Chloramination			Minot WTP	
Rank	1	1	1	1	4		1	5
D	Pre-treatment***	Microfiltration	UV	Chlorination-Chloramination			Minot WTP	
Rank	1	2	1	1	5		1	6

*Minot WTP will be upgrade under various alternatives; 1=current operation continues, 2=upgraded beyond current operating specifications.

**Depending on media of choice, risk reduction score may be increased.

***If pre-treatment consists of coagulation-flocculation-sedimentation, rank score as indicated. If otherwise, rank score adjusted accordingly.

Following the assignment of risk reduction credits to each compartment within each alternatives, component scores were summed to yield total risk reduction credits. On the basis of this categorical analysis, the current menu of alternatives yielded a range of risk reduction credits achieved within-basin for each system—in ascending order, Alternative A < Alternative B < Alternative C < Alternative D. When considered from source to terminus, incorporation of risk reduction outcomes anticipated for treatment at Minot WTP, and the total risk reduction credits in ascending order are Alternative A < Alternative B < Alternative C < Alternative D. Given the similarities in proposed designs for each alternative, the analysis of risk reduction relative to preliminary design suggests that each system's risk reduction credits might provide sufficient margin for accepting risks associated with biota transfers consequent to any system's failure, if costs were incorporated into future engineering design analysis. Risks associated with water transmission pipelines are shared across alternatives and are not discriminating factors in this analysis of failure risks linked to water conveyance. As noted earlier, when operating practices related to treatment regimens are incorporated into final designs, differences in alternatives may be realized and treatment-conveyance interactions should be evaluated as part of future engineering analyses.

In the current analysis, a number of uncertainties and assumptions regarding each alternative and risks associated with these alternatives must be incorporated into interpretative context for refining subsequent iterations of risk reduction analysis. While the current analysis of risks acknowledges differences among alternatives, the summary findings reflect assumptions of risks being identical across systems, e.g., risks of pipe breaks as measured by "breaks per pipe-mile per year" are assumed identical under potentially different operating conditions conditioned on treatment processes incorporated into final designs. Future engineering risk analysis may refine this assumption to capture differences across locations and component parts of the current transmission system, including control and pressure relief valves located at critical locations along the pipeline as configured.

While this preliminary risk reduction analysis helps discriminate among alternatives, system failures should also be considered in developing risk managements plans. In part, the preliminary failure analysis that follows in Section 3.4 complements a similar analysis completed for RRVWS project (USGS 2006). Given the similarities in project drivers—concerns related to unintended biota transfers associated with interbasin water diversions—that earlier investigation completed by USGS (2006) provides data and existing information critical to the failure analysis for the NAWS project.

3.4 Biota Transfer Risks Linked to Control System Failure

Regardless of the engineered system being evaluated, primary causes of system failure may be categorized as being linked to human factors, design or materials failures, extreme conditions or environments, and most commonly, combinations of these reasons. In evaluating natural hazards and failures of natural systems through time, analogous factors may be characterized, most of which are subject to age-related changes in the system or more likely, age-related changes in system components. Potential interaction between engineered control systems and natural resources will be considered as part of the uncertainty analysis linked to preliminary failure analysis of alternatives currently being considered in the NAWS DEIS (Reclamation 2007).

3.4.1 Preliminary Reliability Analysis and the Evaluation of Biota Treatment and Water Transmission Failures. In its simplest statement, the statistical discipline referred to as survival analysis deals with end-of-life events in biological systems and failure in mechanical systems. For our current focus on the evaluation of infrastructure failures in interbasin water transfer systems, the analysis approaches engineering topics referred to as reliability analysis focused on conceptual designs summarized in the DEIS (Reclamation 2007). Death or dysfunction in biological systems and breakdowns or failures in mechanical systems or system components are considered "events" in survival analysis. Much of the work completed in this preliminary analysis of infrastructural failure borrows from existing models of death or failure which are generically termed time-to-event models.

Mathematically, survival analysis considers a range of questions pertinent to the evaluation of events that occur during the "life history" of a system regardless of whether that is a biological system at any particular level of organization (e.g., an individual organism or a population of organisms) or a water treatment and transmission system intended to disinfect and transfer source waters via pipeline to another area some distance from source waters. For example, the current investigation's primary focus has been, "what is the failure rate of biota treatment and water transmission systems as envisioned in conceptual designs for an interbasin water diversion as summarized in the DEIS?" Even in a conceptual design, preliminary analysis of infrastructure failure should benefit natural resource managers and environmental decision-makers regarding the system's characteristics that would likely increase or decrease the odds of survival, or more pointedly, the odds that biota transfers would be realized in the event of control system failure.

Failure analysis applied to this preliminary evaluation reflects the underlying assumption of survival theory—failure occurs only once for each system. Recurring-event or repeated-event models for, e.g., repairable systems, relax that assumption, yet for biota transfers the "fails once" assumption may be a sufficient, but conservative assumption. Although repeated trials in any biota transfer or species invasion are common to the dispersion and establishment of sustainable populations process (see USGS 2005a and references therein), it is possible that a single incursion may yield a successful outcome associated with a single system failure. Through time-in-service, these "one-time failures" may also be viewed as recurring events which are relevant in systems reliability. Regardless of the "fails once" or "repeated failures" assumptions necessary in the analysis or interpretation of outcomes, the current implementation of failure analysis reflects a long history of application to engineering systems evaluation, which is reflected in the brief background that follows in Section 3.4.2.

3.4.2 Reliability Analysis and Life Distributions. A variety of methods have been developed to support failure analysis, particularly when applied to risk reduction evaluation and risk management. Reliability theory developed apart from probability and statistics, yet its application to a range of engineering and natural resource management issues assures analysis commensurate with the available data (see, e.g., Tung et al. 2006, Pukite and Pukite 1998, Muhlbauer 2004, Kleiner et al. 2005, Grayman et al. 2001, Cromwell et al. 2002, Cesario 1995). For example, each of the control systems advanced in the DEIS as alternatives to achieve an interbasin water diversion are, at first glance, examples of "repairable systems" having a history that provides *a posteriori* estimates of failure rates or lifetime distributions, e.g., for components of the system that are non-repairable and fail over time. The reliability of any system reflects the reliability of its components. This building up to the system from the individual components will initially be considered in terms consistent with the design specifications, e.g., specific types of water treatment (e.g., pre-treatments followed by UV treatment or a membrane process) and specification of pipeline components such as type of pipe and its dimensions throughout the transmission system. Such a "bottom-up" method can be subsequently refined, if specifications change and as greater specification is gained through the project's development.

System failures and failure rate (ht(t) or λ) is time dependent, and lifetime plots of system reliability are generally depicted by the idealized "bath-tub curve" (Figure 24; see also USGS 2006 and references cited therein).

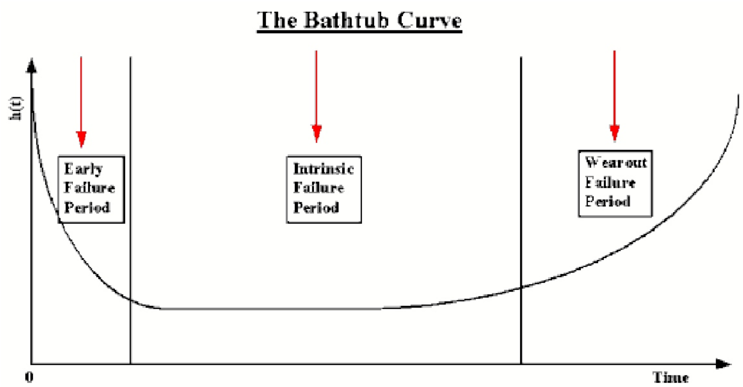


Figure 24. Ideal "bath-tub curve" represents a hazard function characteristic of many system's lifetime distribution or hazard function (original figure modified from NIST source).

The bath-tub curve is often modeled by a piecewise set of three hazard functions,

$$h(t) = \begin{cases} c_0 - c_1 t + \lambda, & 0 \le t \le c_0/c_1 \\ \lambda, & c_0/c_1 < t \le t_0 \\ c_2(t - t_0) + \lambda, & t_0 < t \end{cases}$$

While the bath-tub curve is useful, not every product or system follows a bath-tub curve hazard function (see USGS 2006).

USGS (2005a,b, 2006) provided background on the analytical tools applied to this preliminary analysis of system failure, especially as that relates to biota transfers. While conditioned on the conceptual designs currently identified in the DEIS (Reclamation 2007), the preliminary forecasts characterized in this preliminary analysis may be refined by applying these analytical tools to more fully specified designs, wherein existing data more fully characterize the water treatment and water transmission functions of the control system. Much of the preliminary analysis completed in the current investigation is focused on graphic output typical of systems such as those identified in DEIS (Reclamation 2007). Much of that graphic analysis was considered in detail in USGS (2006), which may be of interest to the reader wanting more detailed discussion of analytical outcomes in the current investigation. While results herein should be considered preliminary, they are sufficient to characterize differences among alternatives currently being considered for NAWS (Reclamation 2007). Depending on the risk tolerance of Reclamation and stakeholders, these preliminary forecasts may also be sufficient to eliminate alternatives from further consideration, identify alternatives warranting future consideration, or advance alternatives currently not captured by DEIS (Reclamation 2007).

Given the long history of graphic and quantitative analysis supporting reliability evaluations for water systems such as those advanced in the DEIS (Reclamation 2007), the heuristic tools brought to earlier USGS investigations (USGS 2005a,b, 2006) have been key to the current analysis of risks associated with biota transfers linked to system failure. While numerically based on existing data and projections derived from Weibull analysis (see USGS 2006; see also Abernethy 2000, Murthy et al 2004, Reliasoft 2005a), outcomes projected in Section 4 are based on a simple scenario reflecting nominal system function throughout a 10,000-day lifetime (see USGS [2006] for additional background). Forecasts of control system lifetime developed in USGS (2006) illustrated a scenario-based analysis of risks typical of many engineering systems (see, e.g., Abernethy 2000, Barlow 1998, Barlow and Proschan 1996, Blischke and Parbhakar Murthy 2000, Lawless 2003, Lee and Wang 2003, Meeker and Escobar 1998, O'Connor 2002, Rausand and Høyland 2004, Tung and Melching 2006) and biological systems (see Section 4 of this report; see also Petrovskii and Li 2006, Caswell 2001, and USGS 2005a,b, 2006, Appendix 1).

3.4.3 Failure Analysis of Interbasin Water Transmission Pipeline and Biota Treatment and System. Section 2 presented a summary review of materials and processes characteristic of the conceptual systems identified as alternatives in the DEIS (Reclamation 2007). Here, we develop a preliminary analysis of a control system comprised of a conveyance module and a biota treatment module which follow a simple life-time model consistent with the bath-tub curve characterized in the preceding section.

Ductile iron pipe (DIP). Ductile iron pipe (DIP) was selected for construction of the water transmission pipeline connecting source water intake at Lake Sakakawea to Minot WTP. DIP is highly regarded for its strength and load bearing capacity, which is reflected in DIP's frequent application to water transmission and distribution needs in the recent past. DIP is a favored pipe material, because of its strength and rigidity. However, DIP is heavy and when unprotected, is highly subject to corrosion from the inside and the outside. Depending on soil conditions, DIP should also be installed with cathodic protection to assure normal service life. A variety of joints are used to join individual sections of DIP in buried applications, with bell and spigot (O-ring push-on) and mechanical joint (MJ) connections the most common (see, e.g., Moser 2001, Antaki 1999, 1997, AWWA standards and manuals as applicable).

DIP is usually encased with polyethylene, cathodically protected, and cement-mortar lined to prevent corrosion. For the water transmission pipeline common to each of the NAWS alternatives, pipe diameters were limited to 30 inch and 36 inch stock. Underground sections are constructed using bell-and-spigot joints; the spigot end of one pipe section is pushed into the bell end of an adjacent section. A rubber-ring gasket in the bell end is compressed when the two sections are joined, creating a watertight, flexible connection. Flanged and bolted joints are used for above-ground installations.

Pipeline failures. Table 8 summarizes general processes and attributes linked to failures in buried pipelines (see also USGS [2005b, 2006]). For example, time-independent attributes associated with mechanical damage or incorrect installation may occur in treatment modules and processes as well as pumps, valves, and gates. Failures associated with time-dependent attributes may similarly be linked to built-system components, e.g., corrosion in valves and gates, or material failures in joints between gates and pipes. Some of these failures would increase risks of biota transfer, e.g., by enabling transfers or increasing susceptibility of receiving system, while others would decrease those risks, e.g., through impaired performance of the delivery system.

From a technical perspective, USGS (2006) provides a foundation for this preliminary analysis through a brief overview of fluid dynamics, since any system selected to meet the water demands of the Souris River basin must reflect processes primarily governed by the fluid mechanics of water flow through pipes. Failure in pipes and mechanical components within the control system may be root-causes of failures in water-transfer systems, which directly or indirectly will reflect hydraulic factors in the system. Such failures potentially mediate releases of biota coincidentally associated with water delivery, e.g., interaction of pressure transients and age-related condition of treatment and conveyance components of the system. The reader is referred to USGS (2006), if more detailed background on the potential root-causes of control system failure linked to fluid mechanics and dynamics are sought. Once control systems are identified for NAWS, these systems would be amenable to evaluation using hydraulic models for higher resolution analyses of failure risks characterized by component-specific empirical data.

General mechanisms linked to infrastructure failure are also summarized in USGS (2006), particularly sources linked to increased or decreased risks associated with:

- corrosion,
- fatigue,
- materials defects, and
- earth movements (through, e.g., frost heave and earthquakes)

which would be risk factors serving as root-causes. These primary factors linked to control system failure are imbedded in this preliminary analysis of system failures based on a simplified control system consisting of a 3-component series that includes (1) an intake component, (2) a treatment component, and (3) a transmission component. This preliminary analysis relies upon empirical data and existing information collected and compiled as noted in Section 2, then considers those empirical data in exponential and Weibull models developed in USGS (2006). The link between control system failure and biota transfers potentially resulting from such failure is considered through a narrative analysis of risks, which is subsequently placed within the context of landscapes or habitats at-risk.

Exceptions to preliminary analysis. Given the design parameters currently developed for the action alternatives summarized in the DEIS, some factors noted in Table 8 will not be considered in the following preliminary analysis. An absence of consideration, however, should not be inferred as their being insignificant sources of risks of failure associated with:

- Third-party actions
- Operator actions

Table 8. General listing of concerns related to failure analysis for buried pipelines (adapted from EPRI 2001).

Time-dependent Attributes

External Corrosion (soil interactions with pipe exterior)
- General corrosion
- Localized corrosion (pitting, crevice, and intergranular attack)
- Microbiologically-influenced corrosion
- Galvanic corrosion
- Environmentally-assisted cracking and corrosion fatigue
- Stray current

Internal Corrosion (water interactions with pipe interior)
- General corrosion
- Localized corrosion (pitting, crevice, and intergranular attack)
- Dealloying
- Microbiologically-influenced corrosion
- Galvanic corrosion
- Environmentally-assisted cracking and corrosion fatigue

Fatigue (pipe material aging)
- Pressure cycling (with associated pressure surges)
- Thermal cycling

Heavy fouling/clogging (deposition on pipe inner walls)

Time-independent Attributes

Mechanical Damage
- Outside party (e.g., other vendors)
- Installation
- Previously damaged

Incorrect Operations
- Operator error
- Incorrect operating procedure
- Over pressurization (potentially yielding pressure surge, e.g., upon correction)

Outside Force
- Earth movements
- Heavy rain, floods

Materials Attributes

Manufacturing Related
- Defective Pipe Seam
- Defective Pipe
- Wrinkle bend or buckle
- Stripped threads/coupling failure

Welding Fabrication Related
- Defective pipe girth weld
- Defective long seam weld

Equipment
- Gasket O-ring
- Control/relief equipment malfunctions
- Seal/pump packing failure
- Miscellaneous

The range of potential breaches to nominal system performance are numerous, and once alternatives of choice have been identified, fully developed engineering designs can incorporate quality assurance programs to minimize failures linked to materials, construction, and installation of control system components that follow best available guidance available (see, e.g., ASCE guidance in place [ASCE 1998] or under development, e.g., http://www.asce.org/instfound/techcomm_pld_location.cfm). Technical and management practices illustrated by these guidance documents reflect an awareness of

- pipeline location practices and procedures including application of survey techniques and assessment of environmental impact;
- pipeline installation methods including both normal and special techniques; and
- quality assurance, proof testing, and inspection practices on constructed pipelines, and to cooperate with other organizations in gathering and disseminating this information to the profession.

In addition to failures linked to out-of-specification materials or construction practices, evaluation of failures potentially linked to malicious actions of third parties may also be incorporated into detailed engineering plans. Given the heightened awareness of water-system security, much of the available guidance reflects water utility concerns; however, the water treatment and water-transmission system's detailed design may benefit from relatively recent compilations by, e.g., Murphy et al. 2005, Hogan and DeBoer 2005, M.B. Corporation 2004, and May 2004. Guidance to secure control systems from intentional breaches range from primers on security-related problems common to water transmission and distribution systems to procedures for decision-makers developing policies to address these issues (see Michael Baker Corporation 2004).

Once detailed engineering designs are available, potential threats and the system's vulnerability to those threats can be considered. For example, plans could be developed for proactive crisis management, emergency preparedness and disaster planning, including emergency response and response team coordination, as well as communications with first responders, news media, and public officials. These security-related planning efforts are merely acknowledged in this preliminary failure analysis, but can be more fully developed as integrated features of engineering designs wherein a HACCP process may help secure water transmission systems by

- identifying points of potential intrusion,
- integrating evaluation of consequences of system failure (e.g., as breach event during unperturbed system performance as in, e.g., "short circuiting" in membrane treatment, or malicious destruction of transmission lines or components),
- recommending enhancements to improve security of existing components, e.g., Lake Sakakawea as source water, and
- recommending design considerations for enhanced security of new infrastructure or future additions to initial-build components (e.g., extension of initial-build water transmission lines to the distribution network envisioned as part of NAWS).

It must also be noted that routine practices, e.g., operational flushing to maintain water freshness or disinfection residual, are not explicitly incorporated into this preliminary analysis. However, these routine elements in O&M procedures would currently be captured by the preliminary analysis developed in this report.

Fluid Dynamics, Leaks, Breaks, and Bursts. Avoiding sudden pipe breaks and bursts in water transmission pipelines such as any of those identified in the DEIS involves a long-term commitment of resources. Service interruptions, the cost of repair and damage to surrounding property, and infrastructure associated with the system operation require dedicated infrastructure management plans. For example, costs associated with the pipeline breaks can be reduced by minimizing the time required for detecting and locating a break. While the preliminary analysis considered in this investigation does not consider hydraulic models better suited for analysis of a fully developed engineering design, the failure analysis initiated by this report considers the control system's hydraulic attributes key to the analysis of failure, particularly as those relate to pipe leaks, breaks, and bursts. In the current investigation, distinctions among these conveyance-related sources of water loss are considered relative to the system's capacity to "make up" for loss of head pressure.

Leaks in piped water occur largely as undetected contributions to water loss, primarily because these losses occur within the operational norms of the system. That is, the variance in hydraulic characteristics of the water transmission system does not routinely allow detection of leaks in conveying water from source to receiving area. Leak tests may be incorporated into O&M schedules, but unless specific tests are implemented, the force behind moving water within the system is sufficient to maintain water flows at given pressures despite the leaks. Leaks may occur beyond a simple measurement related to operating pressures and maintenance of nominal flows. For our purposes, the distinction between leaks and breaks may be characterized as being one where compensatory responses must be made to compensate for water loss taps to system head. In contrast, pipe bursts are simply breaks wherein system compensation is not possible or not practical, and system integrity is jeopardized sufficiently to warrant partial or complete shutdown.

Although the preliminary failure analysis summarized in this section considers system performance as an oversimplified binary state—control system of water treatment and water transmission works per specification and is online, or control system of water treatment and water transmission does not work per specification and is offline—an engineering analysis focused on alternative(s) of choice would likely increase the resolution of potential failures occurring in the system. For example, pressure transient monitoring may be more fully developed in a hydraulic analysis once the specifications for the water transmission system are resolved, and would provide support for developing monitoring programs for detecting and locating breaks in pipelines. Various hydraulic models have been proposed to detect leaks in water distribution systems (see, e.g., Pudar and Ligget 1992, Ligget and Chen 1994, Liou and Tian 1995, Liou 1998, Andersen and Powell 2000), yet few have been field tested or validated (Misiunas et al. 2005). Similarly, methods to evaluate "leak-before-break" behaviors may also be available that would sufficiently characterize the system of choice, and empirical data, e.g., hydrostatic burst tests, may be available for line pipes. Thus, the control system's engineering design could be responsive to stakeholder concerns.

Pipeline failure. Pipelines serve to move many commodities, ranging from highly hazardous gases and petroleum products to irrigation and water intended for municipal and industrial use. Across many years of service and across this range of commodities, pipelines have established performance and safety records, but inevitably, failures have occurred and have been linked to a number of causes. These events range from being relatively benign, to inconvenient, to catastrophic, and despite a range of regulations that have lead to standards and codes guiding the installation and operation of pipelines, failures persist. For example, pipeline wall thicknesses are specified, based on allowable pressure in the line and on the allowable hoop stress for the pipe material (Gagliardi and Liberatore 2000, AWWA 1999a, Mays 1999, 2000). Also, as part of the construction and inspection process, pipelines are pressure tested and materials are subject to nondestructive tests to assure within-specification condition prior to being placed in-service. Pipelines are usually hydrostatically stressed to levels above their working pressure and near their specified minimum yield strength (see, e.g., Larock et al. 2000, Mielke 2004, Mohitpour et al. 2005, Muhlbauer 2004, Reed et al. 2004, Tullis 1989).

Despite standards and codes supporting construction and operation of pipelines, pipeline failures of various magnitudes occur, frequently linked to mediating factors such as

- External or internal corrosion
- Fatigue cracks
- Material defects
- Weld cracks
- Improper repair welds
- Incomplete fusion
- Hydrogen blistering
- Mechanical damage

Water leakage and pipe breaks. One of the most common problems is water loss, especially from a distribution system. In most water distribution systems, some percentage of the water is lost in transit from treatment plants to consumers; water loss typically ranges between 5% and 20% of production (AWWA 2003a, Grigg 2005, Kirmeyer et al. 1994, Kleiner et al. 2005, Mays 2000). Although transmission systems may be simpler in design, e.g., fewer customer service taps to pipeline, leakage is usually present in any water transmission system. There are many possible causes of leaks including:

- pipe material deterioration
- partial or total failure of pipe joints
- earth movements (e.g., frost heaving or earthquake)

and frequently, a combination of factors leads to occurrence of leaks. Leakage occurs in various components of a system, including transmission pipes, fittings and connections within the pipe system, pipe joints, and valves. The material, composition, age, and methods joining system components influence occurrence of leaks, which may lead to breaks and bursts. Causes of leaks include corrosion, cracks, material defects or failure due to deterioration over time, faulty installation, inadequate corrosion protection, ground movement over time due to drought or freezing, and repeated excessive loads and vibration from road traffic. For example, old pipes within a system may leak water through corroded areas, cracks, and loose joints which may develop into pipe bursts, resulting in sudden loss of water pressure and flooding. Although performance criteria will vary with engineering experience and on system function (e.g., transmission function versus distribution function), a "reasonable goal" for pipe break rate in water distribution systems in North America has been estimated at 25 to 30 breaks per 100 miles of pipe per year (15 to 19 breaks per 100 km; see AwwaRF 1995). Given differences between water transmission and water distribution networks, these goals are primarily noted to provide interpretative context for this preliminary analysis.

Common causes of pipe breaks. Cold temperatures frequently lead to increased depths of freezing in the soil column, which is often linked to breaks in water pipes. In areas prone to increased freezing depths and other aggressive soil conditions, secondary protection may be installed inside metallic pipes, e.g., such as pipe coatings or plastic sleeve liners. A simple list of causes linked to pipe corrosion include:

- metal pipe material
- interactions between pipe and soils
- soil properties and contamination
- difference in soil moisture regimes surrounding pipe
- soil pH
- microbial interactions (internal and external to the pipe)
- pipe-to-pipe dissimilarities, e.g., unions between pipes of fabricated from different materials
- differential aging of pipe, including routine O&M replacement schedules that effectively mix new pipe with old pipe
- pipe surface imperfections (e.g., associated with pipe manufacture or installation)
- interactions related to hydraulic-system age (including stress corrosion)
- stray currents

Pipe corrosion is a common root-cause or contributing factor to pipe failure and may be most likely to affect transmission system performance.

3.5 General Overview of Failure Mechanisms and Countermeasures

In this section we briefly characterize failure mechanisms that have previously been detailed as likely root-causes or contributing factors to control system failure, and countermeasures available to offset these failure mechanisms (see USGS 2006).

3.5.1 Corrosion control. Corrosion will be the most likely cause or contributing cause to failures in water transmission and distribution networks, especially following a system's start up and entry to useful life (see bath-tub curve, Figure 24). Depending on its quality, water will vary in its corrosivity with respect to interactions with metal components in the system, e.g., pumps, pipes, gates, and valves. For example, rust and tuberculation of DIP and storage reservoirs may diminish system performance, e.g., tuberculation can dramatically increase the friction loss and reduce the carrying capacity of a transmission pipeline. Carbon dioxide (CO_2) dissolved in water will react to form carbonic acid (H_2CO_3) which contributes to corrosion, as does dissolved oxygen, especially if water alkalinity is low. Water corrosivity is also influenced by relationships between the pH and the alkalinity (see, e.g., Peabody 2001, Roberge 2000). Buried structures such as pipes are invariably exposed to corrosive soil environments which must be considered early in engineering design efforts anticipated as outcomes of our preliminary analysis.

3.5.2 Coatings and Lining Systems. External coatings and internal linings extend the service life of pipelines by minimizing leaks due to corrosion. Hence, both external and internal countermeasures are incorporated into pipeline design, since each means of control addresses different corrosive environments influencing the long-term service life of the system, e.g., internal lining would not mitigate external corrosion activity which could continue unimpeded in the absence of external coatings or wrappings of offset corrosive environments associated with soils and backfill. Internally lined and externally coated pipes control corrosion of ferrous components in the pipeline system. Pipe coatings and linings in concert with cathodic protection are considered an economical solution to both external and internal corrosion. For example, cement mortar lining is routinely used to control internal corrosion in pipelines relying on ferrous pipe, and in both new installation and in rehabilitation of existing service lines, buried piping will be cleaned and lined with cement or other materials as appropriate to a specific application.

External coatings. External countermeasures to corrosion in a pipeline system must consider native soils in the area and fill materials used during installation. The use of select, non-corrosive material (such as sand or limestone) for bedding and backfill represents one countermeasure commonly incorporated as “trench improvement” in constructing water transmission and distribution systems. Trench improvement generally provides good structural support and helps delay the onset of corrosion activity, in part by offsetting stresses associated with loads experienced under nominal operation. However, trench improvement does not provide long-term protection to the pipe, particularly in highly aggressive soil environments. Water permeation through native soils immediately adjacent to the trench provides moisture to backfill over time, and potentially initiates corrosive events adversely affecting buried pipe and fittings. Thus, trench improvement is part of corrosion control that complements practices that apply external coatings or wraps to pipe during the installation process. Polyethylene encasement is the most frequently relied on external coating, most often as a pipe wrap, and is an effective method for corrosion prevention of ferrous pipe. Standards specify materials and installation practices for pipeline installation, e.g., pipe sections may be specified with a dielectric coating system consisting of machine applied, three layer polyethylene spiral tape wrap system conforming to AWWA Standard C214, and pipe fittings, specials and field joints would be similarly specified with a dielectric coating system consisting of a three layer polyethylene tape system conforming to AWWA C209.

Linings. Complementary countermeasures provide for corrosion control for internal environments common to water transmission and distribution pipelines. In water transmission and distribution systems, pipelines and other structures are routinely coated with interior lining systems of cement mortar or epoxy materials. Pipelines and other structures routinely are coated with interior lining systems to isolate the substrate from corrosive internal environments, e.g., cement mortar lining of pipe. Along with technical advances in materials used in manufacture of pipes, research on lining requirements for pipe and fittings has resulted in practices for installation of linings to meet many different applications. Several types of linings are available, the most common being cement mortar lining. Pipe and fittings may be lined, most often specified by AWWA C104 for cement-lined pipe and fittings, AWWA C110, C115, or C151 for asphaltic-lined pipe, or fusion-bonded epoxy lining for 4"-16" Fastite fittings, following AWWA C116. The principal standard covering cement mortar lining is ANSI/AWWA C104/A21.4.

Cement mortar lining. Cement-mortar linings have been successfully used to protect the interior of ferrous pipe and fittings for over 80 years. In general, cement linings of various formulations prevent tuberculation by creating high-pH microenvironments at the pipe wall. These alkaline pH conditions serve as a barrier to the potentially corrosive conditions associated with water being conveyed through the system.

Physical properties of ferrous materials such as those characteristic of DIP change relatively little with time, although age-related changes in structural material associated with external and internal corrosion will undoubtedly affect the structural integrity of the pipe. Cement-mortar linings and special linings have eliminated or at least reduced concerns associated with internal corrosion, especially in new installations. Soils vary geographically at varying spatial scales with respect to their corrosivity, and final route will undoubtedly rely on, e.g., soil evaluation procedures outlined in Appendix A of the ANSI/AWWA C105/A21.5 Standard, “Polyethylene Encasement for Ductile-Iron Pipe Systems.” If soils are corrosive, polyethylene encasement is the corrosion protection method normally recommended by the, e.g., Ductile Iron Pipe Research Association (DIPRA) and various manufacturers of DIP. If soils are non-corrosive when tested in accordance with Appendix A of ANSI/AWWA C105/A21.5, or if it is determined corrosive and the pipe is encased with polyethylene in accordance with the standard, ferrous pipe such as DIP could have a life expectancy of more than 100 years. If ferrous pipe is installed in aggressively corrosive environments without protection, its life expectancy would mainly be a function of that environment. To minimize atmospheric oxidation of aboveground ferrous pipe, asphaltic coating is applied in accordance with ANSI/AWWA C151/A21.51 may be incorporated into system designs, although when soils are determined to be corrosive by procedures detailed in Appendix A of ANSI/AWWA C105/A21.5, polyethylene encasement in accordance with the AWWA C105 standard should be installed for corrosion protection.

Cement-mortar lining for ferrous pipe such as DIP and fittings for water service follows ANSI/AWWA C104/A21.4. Most pipe placed in service is cement-lined, and provides improved flow characteristics and protection required against internal corrosion. Cement linings are satisfactory for temperatures up to 212˚F (for asphaltic seal coats, the lining is only adequate for temperatures up to 150˚F). Lining is applied centrifugally with the speed of rotation designed to produce a smooth waterway surface, minimal voids, yet retaining enough moisture for proper curing. Cement-lined pipe and fittings are consistent with ANSI/NSF Standard 61 for potable water contact. Flow tests on cement-lined pipe under varying service conditions have established that the Hazen-Williams flow coefficient remains as expected at about 140, and for cement-lined, large-diameter pipe flow coefficients much higher than 140 are achieved.

3.6 Soil conditions potentially influencing system failures

The type of soil and the general grading conditions at the installation site are important factors in determining foundation construction details, such as footing design, backfill, and drainage. Soils are classified depending on several physical and engineering parameters including their grain size distribution, liquid and plastic limits, organic contents, drainage characteristics, frost heave potential, and swell potential. There are several types of classification systems. The US Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS) categorizes and describes soil types in four large groups depending on Unified Soil Classification System, their estimated engineering behavior, drainage characteristics, frost heave potential, and swelling potential (see USGS 2006). Suggested values for soil bearing capacities, undrained shear strength, and friction angles are presented in USGS (2006), although these values are only estimates intended for construction applications when other data are not available. It is also important to note that soil properties can vary significantly from one site to another and even within a single site. Although all soil factors potentially adversely influencing control system performance are critical to any analysis of risks, soil corrosivity may be highly influential for determining long-term risks of pipeline failure.

3.6.1 Soil corrosivity. USGS (2006) considered corrosion processes, particularly those potentially linked to soil exposures of buried ferrous pipe. In general, corrosion is an electrochemical process by which refined metals return to a native state, provided conditions exist for a corrosion cell to function at the metal-soil interface. Many factors affect soil corrosion activity on ferrous materials in direct contact with soil (Table 9). Soil corrosivity is a complex process, but is generally more severe as soil resistivity decreases below 10,000 ohm/cm, soil pH is below 3 or above 9, and redox potential decreases below 100 mV (a measure of microbial influenced corrosion potential; see USGS [2006]). Other factors such as the presence of chlorides, sulfides, salts, organic materials, different oxygen levels, poor drainage, different soil types and moisture content also contribute to corrosivity. These factors oftentimes vary seasonably, e.g., soil resistivity generally decreases as temperatures rise.

For pipeline routing of the water transmission pipeline key to NAWS alternatives, corrison potential of soils appears to be low to moderate, as illustrated by measures of soil conductivity (Figure 25). Soil conductivity is generally less than 0.4 mmhos/cm and consistently presents at less than 0.8 mmhos/cm. Only occasionally does soil conductivity range greater than 0.8 mmhos/cm in depressional wetlands typical of the prairie potholes. Given corrosion countermeasures incorporated into pipeline construction (e.g., cathodic protection), soils along the pipeline route would not be anticipated as being high risk factors linked to conveyance failures.

Table 9. Risks factors for evaluating a soil's corrosion potential for uncoated steel.

Soil Property	Risk and Associated Limits Characteristic of Soil Property		
	Low	**Moderate**	**High**
Drainage class and texture	Excessively drained, coarse textured or well drained, coarse to medium textured soils; or moderately well-drained coarse textured soils; or somewhat poorly drained, coarse textured soils	Well-drained, moderately fine textured soils; or moderately well-drained, medium textured soils; or somewhat poorly drained, moderately coarse textured soils; or very poorly drained soils with stable high water table	Well-drained, fine textured or stratified soils; or moderately well-drained, fine and moderately fine textured or stratified soils; or somewhat poorly drained, medium to fine textured or stratified soils; or poorly drained soils with fluctuating water table
Total acidity (meq/100g)[2]	< 8	8–12	≥ 12
Resistivity at saturation (ohm/cm)[3]	≥ 5,000	2,000–5,000	< 2,000
Conductivity of saturated extract (mmhos/cm)[4]	≤ 0.3	0.3–0.8	≥ 0.8

[1] After US Department of Commerce, National Bureau of Standards (1957) and USDA (2004).

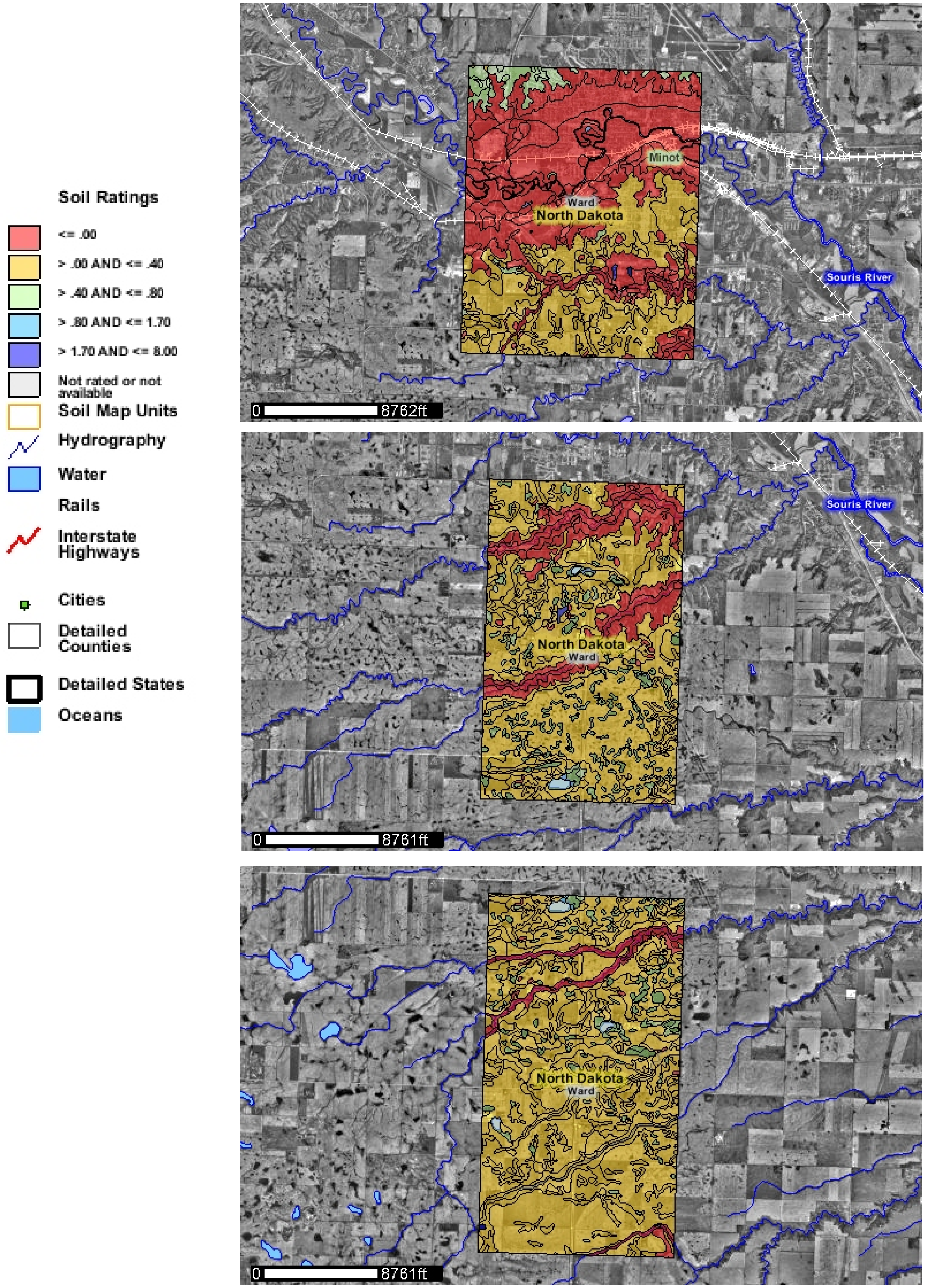
[2] Total acidity is approximately equal to extractable acidity as determined by Soil Survey Laboratories Method 6H1a.

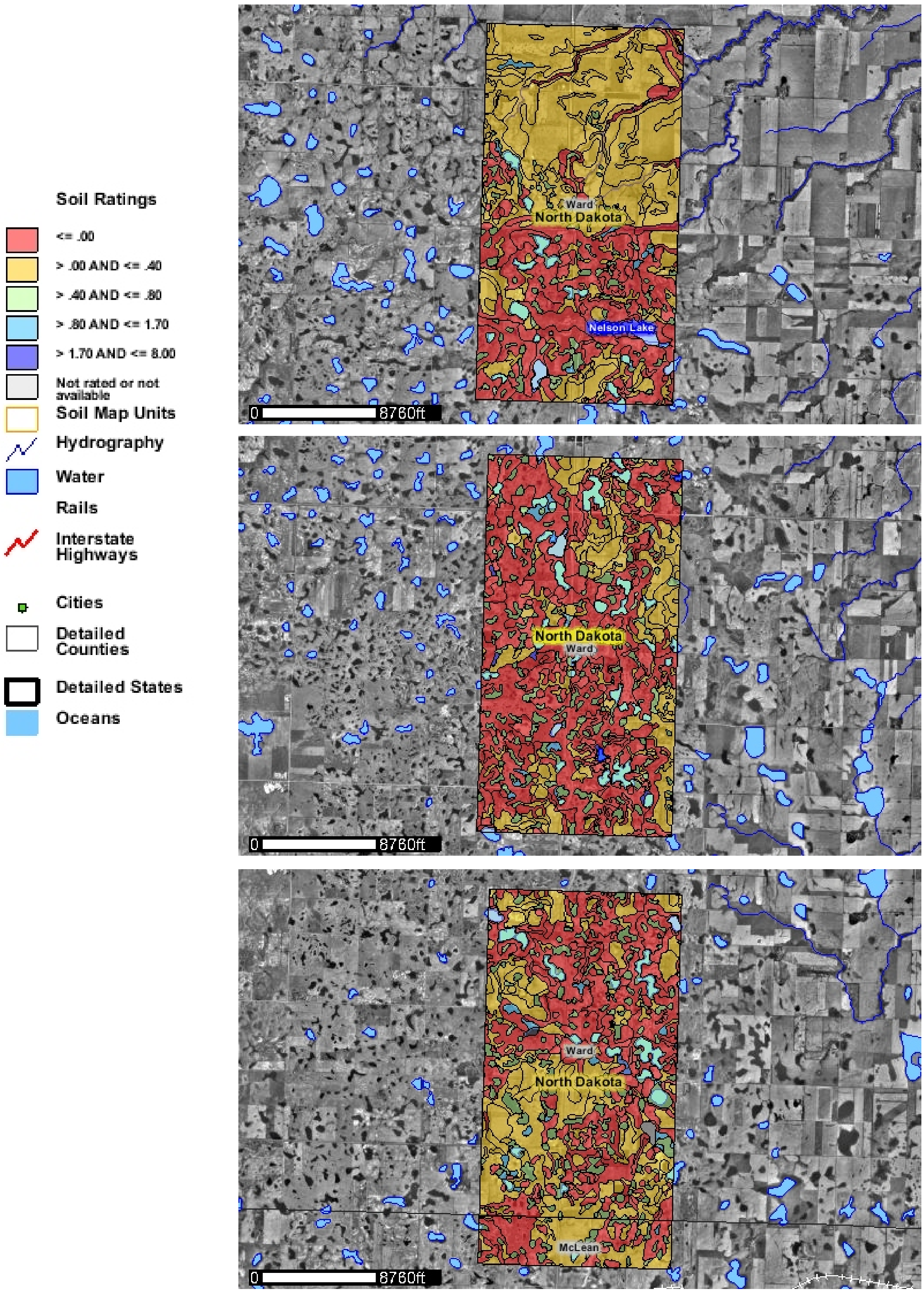
[3] Approximately equivalent to resistivity of fine- and medium-textured soils measured at saturation as determined by Soil Survey Laboratories Method 8E1; resistivity at saturation for coarse-textured soil is generally lower than when obtained at field capacity and may cause soil to be placed in a higher corrosion class.

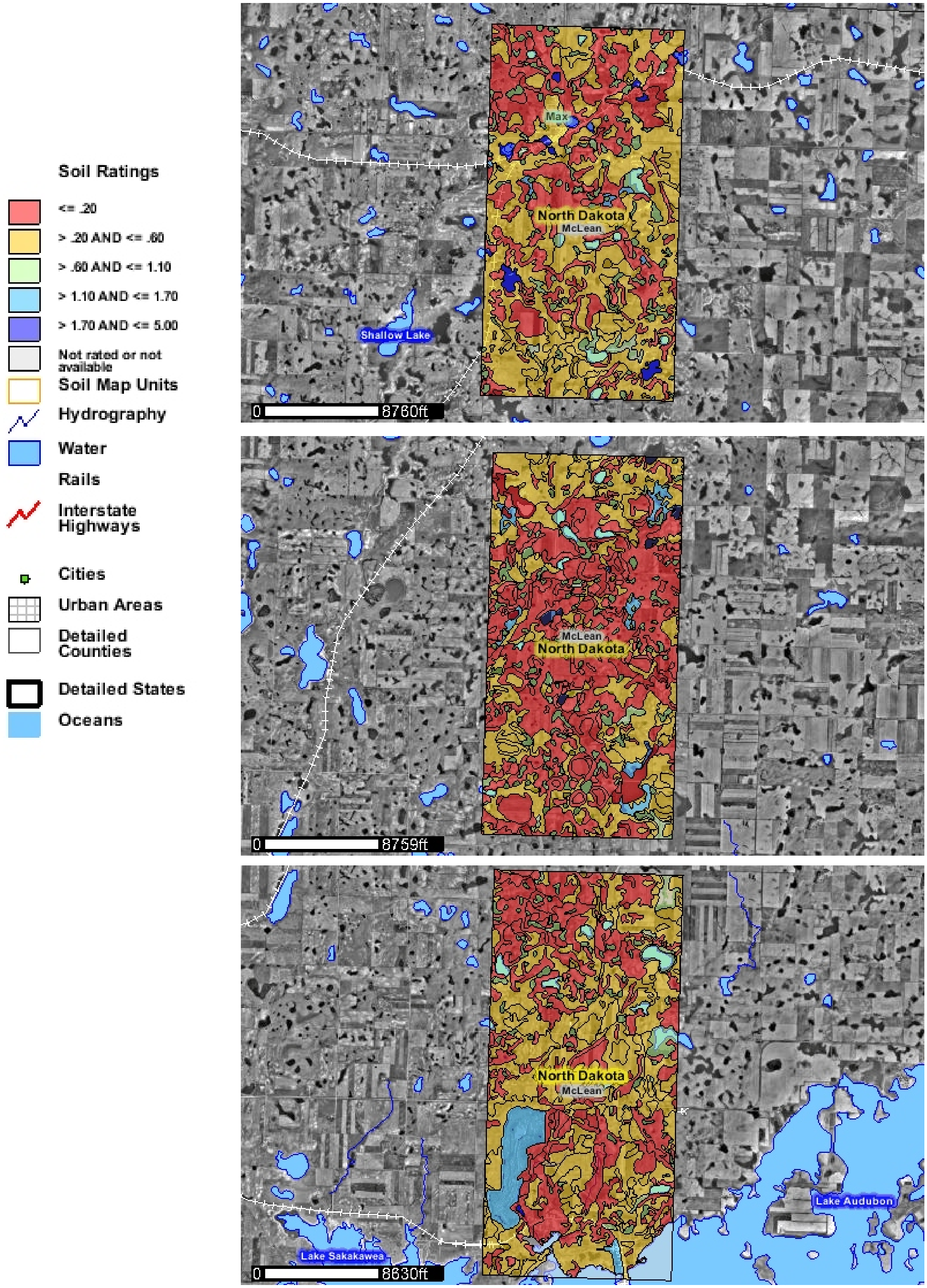
[4] As determined by Soil Survey Laboratory Method 8A1a. The relationship between resistivity of a saturated soil paste (Method 8E1) and electrical conductivity of the saturation extract (Method 8A1a) is influenced by variations in the saturation percentage, salinity, and conductivity of the soil minerals. These two measurements generally correspond closely enough to place a soil in one corrosion class.

3.6.2 Slope stability. Soil slope stability is an important design consideration that is often difficult to predict. A history of slope failures at or near a given location is a strong indication of the presence of a problem, and further investigation and careful design considerations may be needed. A geotechnical engineer can predict whether slope failures are likely to occur at a particular site based on the slope angle, the characteristic drainage and seepage of the site, the shear strength properties of the soils (friction angle or undrained shear strength), and the external loads. Given the elevations along the water transmission pipeline route, slope stability is not anticipated as a high risk factor linked to conveyance failure.

Figure 25. Soil conductivity along the pipeline route connecting Lake Sakakawea with Minot WTP.


Soil Ratings
<= .00
> .00 AND <= .40
> .40 AND <= .80
> .80 AND <= 1.70
> 1.70 AND <= 8.00
Not rated or not available
Soil Map Units
Hydrography
Water
Rails
Interstate Highways
Cities
Detailed Counties
Detailed States
Oceans
Minot
Ward
North Dakota
Souris River
0
8762ft
North Dakota
Ward
Souris River
0
8761ft
North Dakota
Ward
0
8761ft


Soil Ratings
<= .00
> .00 AND <= .40
> .40 AND <= .80
> .80 AND <= 1.70
> 1.70 AND <= 8.00
Not rated or not available
Soil Map Units
Hydrography
Water
Rails
Interstate Highways
Cities
Detailed Counties
Detailed States
Oceans
Ward
North Dakota
Nelson Lake
0
8760ft
North Dakota
Ward
0
8760ft
Ward
North Dakota
McLean
0
8760ft


Soil Ratings
<= .20
> .20 AND <= .60
> .60 AND <= 1.10
> 1.10 AND <= 1.70
> 1.70 AND <= 5.00
Not rated or not available
Soil Map Units
Hydrography
Water
Rails
Interstate Highways
Cities
Urban Areas
Detailed Counties
Detailed States
Oceans
Max
North Dakota
McLean
Shallow Lake
0
8760ft
McLean
North Dakota
0
8759ft
North Dakota
McLean
Lake Audubon
Lake Sakakawea
0
8630ft

3.6.3 Failure associated with earth movements.[9] Earthquakes and frost heaving are the most likely earth movement events considered in this preliminary failure analysis. The northern Great Plains is not particularly active with respect to earthquakes, and when these geological events occur, they are well document and generate reports from the public. Hence, the events tend to be well documented (see, e.g., Bluemle 2002). However, limited seismic activity has occurred throughout the region. For example, in summer of 1968, an earthquake with an epicenter southwest of Huff, North Dakota occurred and sensed over a 3,000-square-mile area, including Bismarck and other central North Dakota communities. USGS National Earthquake Information Center (NEIC) has recorded a number of low-energy seismic events in North Dakota, Minnesota, and environs, with the most widely sensed earthquake occurring in late spring of 1909. That event had an epicenter near Avonlea, Saskatchewan, near the Montana-North Dakota-Saskatchewan border, and was felt throughout North Dakota and western Montana as well as in the adjacent Canadian Provinces. Earthquakes records are compiled by USGS NEIC which indicates a range of events have occurred in the region, including one in southeastern North Dakota in 1872; Pembina in 1900; three in the Williston area in 1915, 1946, and 1982; the Hebron area in 1927; near Havana in 1934; and the Selfridge area in 1947. Earthquakes centered near Morris, Minnesota were felt in southeastern North Dakota in 1975 and 1993.

3.6.4 Soil heave and frost action.[10] While earthquakes would represent extreme events on the northern Great Plains, frost heaving commonly occurs during winters in the northern Great Plains. Damage from frost action results from the formation of segregated ice crystals and ice lenses in the soil and the subsequent loss of soil strength when the ground thaws. For example, frost heave damages highway and airfield pavements, but tends to be less of a problem for dwellings and buildings that have footings which extend below the depth of frost penetration. In cold climates, unheated structures that have concrete or asphalt floors can be damaged by frost heave. Driveways, patios, and sidewalks can heave and crack. The thawing of the ice causes a collapse of surface elevation and produces free water perches on the still frozen soil below. Soil strength is reduced. Back slopes and side slopes of cuts and fills can slough during thawing.

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[9]Suggested reading:

Biek, B., 1997, Earthquakes in North Dakota, North Dakota Geological Survey Newsletter, Vol. 23, No. 1, pp 17-23. Bluemle, J.P., 1989, Earthquakes in North Dakota, North Dakota Geological Survey Newsletter, No. 6, pp 21-25.

Earthquakes in North Dakota, North Dakota Notes, North Dakota Geological Survey website: http://www.state.nd.us/ndgs/Earthquakes/earthquakes.htm

National Earthquake Information Center, United States Geological Survey: http://neic.usgs.gov/
United States Geological Survey, Earthquake Hazards Program: http://earthquake.usgs.gov/

[10] (see Section 618.29, USDA 2003, 2004).

Potential frost action is the rating for the susceptibility of the soil to upward or lateral movement by the formation of segregated ice lenses. It rates the potential for frost heave and the subsequent loss of soil strength when the ground thaws. Soils are categorized into classes in regions where frost action is a potential problem.[11] The classes are low, moderate, and high, and are categorized as

- Low, soils are rarely susceptible to the formation of ice lenses.
- Moderate, soils are susceptible to the formation of ice lenses, which results in frost heave and subsequent loss of soil strength.
- High, soils are highly susceptible to the formation of ice lenses, which results in frost heave and subsequent loss of soil strength.

Freezing temperatures, soil moisture, and susceptible soils are needed for the formation of segregated ice lenses. Ice crystals begin to form in the large pores first. Water in small pores or water that was adsorbed on soil particles freezes at lower temperatures. This super-cooled water is strongly attracted to the ice crystals, moves toward it, and freezes on contact with them. The resulting ice lense continues to grow in width and thickness until all available water that can be transported by capillary has been added to the ice lense and a further supply cannot be made available because of the energy requirements.

Soil temperatures must drop below 0˚ C for frost action to occur. Generally, the more slowly and deeply the frost penetrates, the thicker the ice lenses, the greater the frost heave (Figure 26; see also USDA 2003, 2004). Design freezing index values for the continental US are the number of degree days below 0˚ C for the coldest year during the preceding 10-year period; hence, these values indicate duration and intensity of freezing temperatures. An index value of 250 isoline is the approximate boundary below which frost action ceases to be a problem, and for North Dakota the frost action boundary corresponds closely to the mesic-thermic temperature regime boundary used in Soil Taxonomy. Design freezing index values for North Dakota are generally greater than 3000 (see Figure 26; see also USDA 2003, 2004).

Water necessary for the formation of ice lenses may come from a high water table or from infiltration at the surface. Capillary water in voids and adsorbed water on particles also contribute to ice lense formation, but unless this water is connected to a source of free water, the amount generally is insufficient to produce significant ice segregation and frost heave. The potential intensity of ice segregation is dependent to a large degree on the effective soil pore size and soil saturated hydraulic conductivity, which are related to soil texture. Ice lenses form in soils in which the pores are fine enough to hold quantities of water under tension but coarse enough to transmit water to the freezing front. Soils that have a high content of silt and very fine sand have this capacity to the greatest degree and hence have the highest potential for ice segregation. Clayey soils hold large quantities of water but have such slow permeability that segregated ice lenses are not formed unless the freezing front is slow moving. Sandy soils, however, have large pores and hold less water under lower tension. As a result, freezing is more

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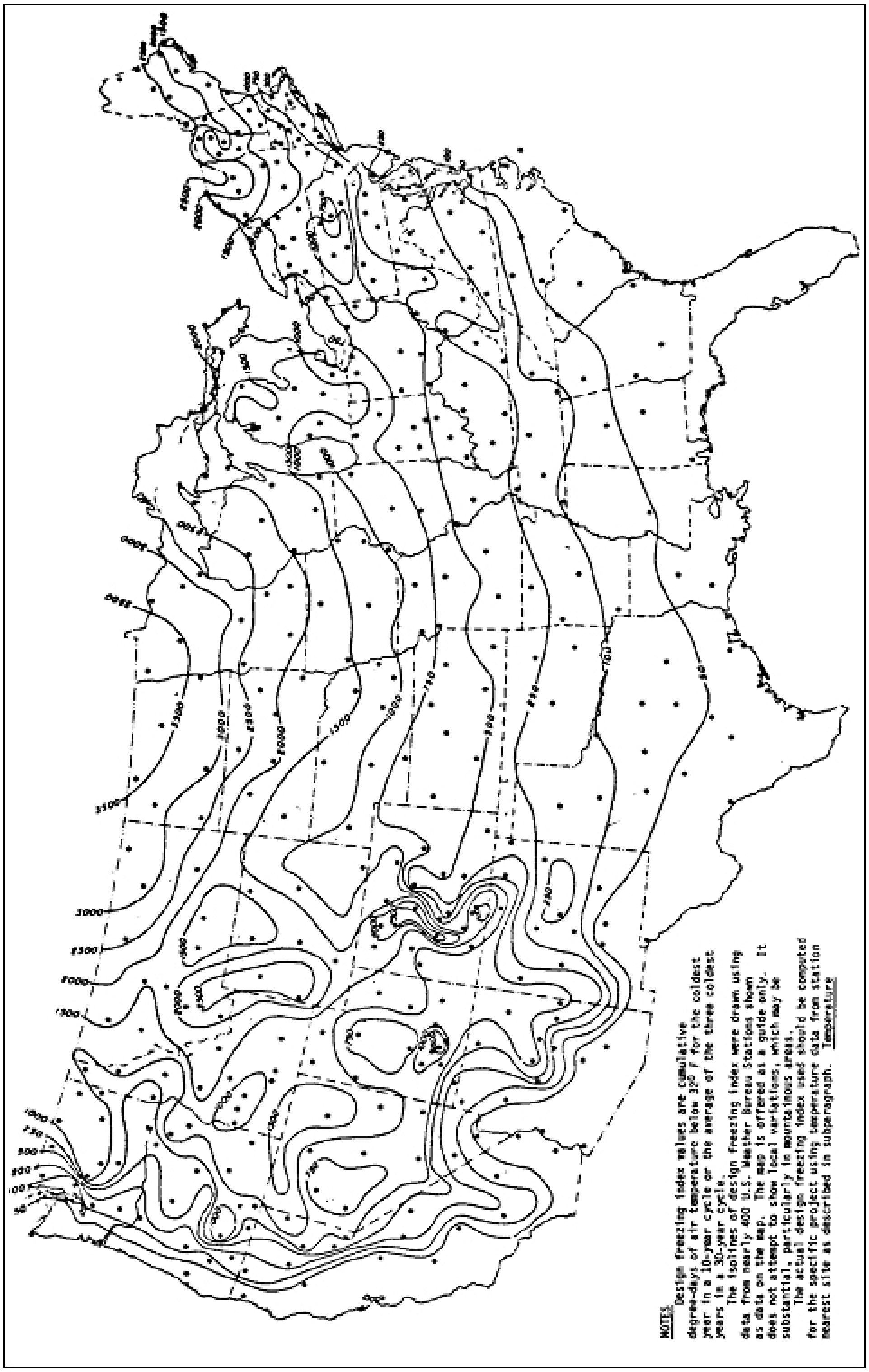
[11](see Exhibit 618-5 in USDA 2003, 2004).

Figure 26. Design freezing index values for continental US (after USDA 2003, 2004).


NOTES
Design freezing index values are cumulative degree-days of air temperature below 32° F for the coldest year in a 10-year cycle or the average of the three coldest years in a 30-year cycle.
The isolines of design freezing index were drawn using data from nearly 400 U.S. Weather Bureau Stations shown as dots on the map. The map is offered as a guide only. It does not attempt to show local variations, which may be substantial, particularly in mountainous areas.
The actual design freezing index used should be computed for the specific project using temperature data from station nearest site as described in subparagraph. Temperature

rapid and the large pores permit ice masses to grow from pore to pore, entombing the soil particles. Thus, in coarse-grained soils, segregated ice lenses are not formed and less displacement can be expected.

Estimates of potential frost action generally are made for soils in mesic or colder temperature regimes. The estimates are based on bare soil that is not covered by insulating vegetation or snow, and reflect the moisture regime of the natural soil. The ratings can be related to manmade modifications of drainage or to irrigation systems on an on-site basis. Frost action estimates are made for the whole soil to the depth of frost penetration, to bedrock, or to a depth of 2 meters (6.6 feet), whichever is shallowest. USDA (2004)[12] provides a guide for making potential frost action estimates based on moisture regimes and family textures as defined in Soil Taxonomy. Although soils along the pipeline route likely present significant risk factors related to frost heave potential, countermeasures should have been captured in the construction of the pipeline, e.g., depth and fill requirements specified for the region.

3.7 Failure Analysis and Risks of Biota Transfer

From a numbers perspective, the preliminary failure analysis for the engineering system captured in the conceptual designs characterized in DEIS (Reclamation 2007) may be simplified as a 3-step process to move water from Missouri River basin to the Souris River basin in North Dakota. As a first approximation of system failure, an engineer or a reliability analyst would characterize this 3-step process by a "bath-tub curve" (recall Figure 24). Mathematically, the engineer's bath-tub curve characterizes a "life-time" distribution of failures similar to life tables common to biological and ecological processes (see, e.g., Fleming and Harrington 1991, Meeker and Escobar 1998, Hosmer and Lemeshow 1999, Caswell 2001, O'Connor 2002, Lee and Wang 2003, Lee 1992, Smith 2002, Rausand and Høyland 2004, Reliasoft 2005a,b).

Preliminary estimates of system failures and analysis of risks of biota transfer. The uncertainties associated with the simple scenario identified here will be considered in Section 4, but elaboration beyond the simple scenario involving source water intake, treatment, and conveyance is better left to more fully developed engineering designs identified as outcomes of the NEPA process, including, e.g., regulatory specification of limiting values or performance criteria necessary for full design. Once an alternative of choice is identified, outcomes from a fully integrated engineering failure and reliability analysis would better serve stakeholder concerns than an endless series of preliminary analyses based on conceptual designs. Hence, in this preliminary failure analysis of alternatives, coarse estimates may help focus on those components of the selected system's lifetime that are most critical in regard to risk of biota releases that might result from infrastructure failure. Preliminary estimates of failure probability for the system are developed to set the stage for linking failures to vulnerable habitats briefly characterized in Section 2, then evaluated in Section 4 along with their attendant uncertainties.

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[12]see USDA 2003, 2004 (Exhibit 618-5).

Given the conceptual designs for alternatives being considered in the DEIS (Reclamation 2007), the simple lifetime distribution scenario developed in USGS (2006) is equally applicable to this failure analysis for NAWS, which suggests categorical risk estimates for system failure as:

- Risk of system failure in “early life” (initial year of operation) would be considered moderate to high, and is conservatively estimated at 1 out of 10,000 for system failure yielding a biota transfer,
- Risk of system failure during “useful life”(bounded between 1-year and up to 20-years service life) would be considered low to moderate, and is conservatively estimated at 1 out of 100,000 for system failure yielding a biota transfer, and
- Risk of system failure during “late life” (beyond 20 years service life) would be considered high to very high, and is conservatively estimated at 1 out of 1000

Bear in mind, regardless of when system failure occurs, these conservative estimates assume that a single system failure will yield a successful biota transfer, and a sustainable population will be established consequent to that system breach. As noted in USGS (2005a, 2006), this fails-once assumption regarding the linkage between biota transfer and establishment of sustainable populations in the receiving area may be possible, but not highly likely, and depends on the spatiotemporal attributes that characterize when and where the failure occurs. While multiple scenarios should be considered in an engineering failure analysis, these conservative estimates have been developed in order to place risk into the same perspective as those developed for RRVWS project.

3.8 Multiple Pathways and Their Role as Competing Risk Factors

Risk factors are generally considered as variables associated with an increased risk of an event such as the occurrence of a disease or an infection—both end-states that dominate the conceptual model formulated in this initial analysis of biota transfer risks linked to interbasin water diversions proposed for NAWS project. As applied in epidemiology and failure analysis, risk factors are correlational and not necessarily causal in character. Although our analysis focused on the characterization of risks directly associated with interbasin water diversions, in order to adequately interpret those risks, the system at-risk had to be considered within the context of initial baseline characterizations reflecting “before-project” conditions. Similarly, competing sources and pathways were considered in order to place project-specific risks within the context of the larger system, including the NAWS service area and potential source areas of biota of concern. While the invasion biology literature is replete with “rules of thumb” based on field observations and “best professional judgments,” there are few fully characterized quantitative data needed to develop an empirically-based probabilistic analysis of invasion events (see USGS 2005a,b). In contrast, as summarized in USGS (2006), control system failures linked to water treatment, containment, or transmission were based on relatively rich data sources, and may be considered as necessary (but not sufficient) steps initiating a project-dependent biota transfer process. As such, control system failure (USGS 2006) and a generalized process characteristic of the biota transfer-species invasion process (USGS 2005a) provided a common ground for evaluating multiple pathways linking sources with various receiving areas of the Hudson Bay basin.

As process components, pathways linking sources with receiving areas are critical to biota transfer, and reflect multiple competing risk factors for each of the biota of concern (see USGS 2005a). Regardless the species of interest, the initial steps of biota transfer and the potential biological invasion or shift in metapopulations are highly dependent on pathways of introduction. National Invasive Species Council (NISC; see NISC 2001) characterized generalized pathways of the invasion process (see USGS [2005a,b; see also http://www.invasivespeciesinfo.gov/toolkit/ pathways.shtml last accessed July 10, 2007), and the current investigation's view of project and non-project pathways were described by fault-probability trees characterized in USGS (2005a), wherein the flows-of-events characteristic of the biota transfer process were posited. Development of fault-probability trees reflected, in part, tools of the system's ecologists, conservation ecologists, and reliability engineers (see USGS 2005a, 2006). As such, those multiple pathways illustrated in USGS (2005a) were consistent with those identified by NISC (2001) in their consideration of pathways and their relationship to the invasion process. From a system's analysis perspective, pathways of the invasion process share many common attributes, e.g., similar pathways potentially serve as links between sources and receiving areas regardless of whether those occur at any one moment in time in the Missouri River basin or elsewhere. NISC (2001) had recognized three generic pathway categories which are consistent with the analytical process that guided the current investigation:

- Transportation-related pathways including various pathways related to the transportation of people, goods, and the transport vehicles themselves (e.g., private and public sector, commercial, industrial, and military vehicles). Specific facets of the transportation category included modes of transportation and shipping materials.

- "Living industry" pathways including various pathways associated with living plants and animals or their by-products, e.g., food-to-market pathways, pathways related to transport of plants and animals, including commercial trade or exchange of plant and animals (such as plant and aquarium trade).

- Miscellaneous pathways were those considered outside the other categories and included various pathways related to other aquatic and terrestrial pathways, ecosystem disturbance, other nonliving animal and plant-related pathways, and natural (no human agency involved) dispersal of previously established populations of invasive species.

Implementing pathways' analysis for the current investigation focused our effort beyond the more global context of NISC, but attributes of pathways common to project and non-project routes are identical to those identified by NISC (see USGS [2005a,b; see also http://www.invasivespeciesinfo.gov/toolkit/pathways.shtml and http://www.invasivespeciesinfo.gov/toolkit/vectors.shtml last accessed July 10, 2007). For example, "Anthropogenic Pathways" (USGS [2005a]) or pathways associated with "Human Agency" (NISC 2001) are a common feature to non-project pathways that are potentially linked to biota transfers potentially yielding species invasions or shifts in metapopulations. Transportation-related pathways include various modes by which initial "beachheads of invasion" could be achieved. While any of those identified in the current investigation or by NISC could provide opportunity, aquatic pathways would be the most likely to prove instrumental in linking the Hudson Bay basin with Missouri River or other adjacent basins. For example, past analyses of aquatic routes likely associated with invasion processes (e.g., Carlton 1993; D'Itri 1997) clearly indicated that multiple mechanisms of biota transfer are participating in large numbers of "trials" through time, e.g., ship and barge traffic on surface waters, recreational boats, and other craft on surface waters or in transit between bodies of water, among other candidate modes of transit. The list is long, and from a competing risk perspective, the sum of these multiple aquatic pathways qualitatively decreases the probability of controlled interbasin water transfers from dominating the overall risk of invasion.

The wide range of potential pathways suggests numerous transfer mechanisms exists, and given the number of trials potentially completed in any given time interval, breaches to system integrity should be anticipated as transfer events. Although characterized as being low-probability events (see USGS 2005a), these breaches in biological security may be inevitable. Indeed, overall risks of species transfers may approach unity with a very low number of successful transfers potentially yielding a successful event, given a very large number of trials occurring in time. Whether these breaches in biological security are sufficient to yield adverse effects in the receiving area depend upon the life history attributes of the transferred agent, exposure of the transferred agent to countermeasures en route, and the conditions of the receiving system at-risk (see USGS 2005a, 2006).

Risks Associated with Potential Interbasin Biota Transfers Directly Associated with Water Diversions. As suggested by NISC and summarized in USGS (2005a), competing pathways that are directly accountable for mediating biota transfer events are numerous, yet our focus in this risk characterization lies with interbasin water transfers. That is, our initial estimates of risks associated with intrabasin biota transfers are concerned only with events directly linked to proposed water diversions between the Missouri River and Red River basin. These risks are considered relative to (1) baseline, which refers to the dynamic state of historic and future species invasions realized in the absence of water diversion and (2) competing risks, which refers to interrelated risks that are potentially associated with direct linkages achieved via alternate routes (i.e., direct pathways other than interbasin water diversions).

As a simple model applied to this analysis of competing pathways as risk factors influencing biota transfers, the simulation that follows was derived from the fault-probability trees considered in USGS (2005a) and the failure analysis considered in USGS (2006). Here, the flows-of-events were focused on competing risks linked to project and non-project pathways characteristic of NAWS conceptual designs. For this simulation, control systems characteristic of those alternatives outlined in Reclamation (2007) were generalized as pathways linking biota of concern in source areas of the Missouri River basin with receiving areas in the Souris River basin of the Hudson Bay watershed. Attributes of the "biota transfer directly linked to water diversion pathway" (Pathway 1) reflect performance criteria that guided the failure analysis completed in USGS (2006), which reflected a maximum risk reduction achievable using "best available technology" or "best management practices" consistent with microbial and disinfection by-products (MDBP) rules, e.g., LT2ESWTR and Stage 2 Disinfection By Products (DBP) rule (see http://www.epa.gov/ OGWDW/disinfection/stage2/index.html last accessed July 11, 2007).

The simulation undertaken in this preliminary evaluation of risk factors for competing pathways influencing biota transfers was based on a simple process model illustrated in Figure 27. Here, each of 10, two-step pathways were generally identified as representing the range of pathways listed in Table 3 (see Section 2). For purposes of this simulation, biota transfer was regarded as a certainty, and only pathway values as products of the two-step transfer process (e.g., failure in biological treatment-containment and failure in conveyance steps both occurred) varied over the simulation which was reiteratively solved 10,000 times.

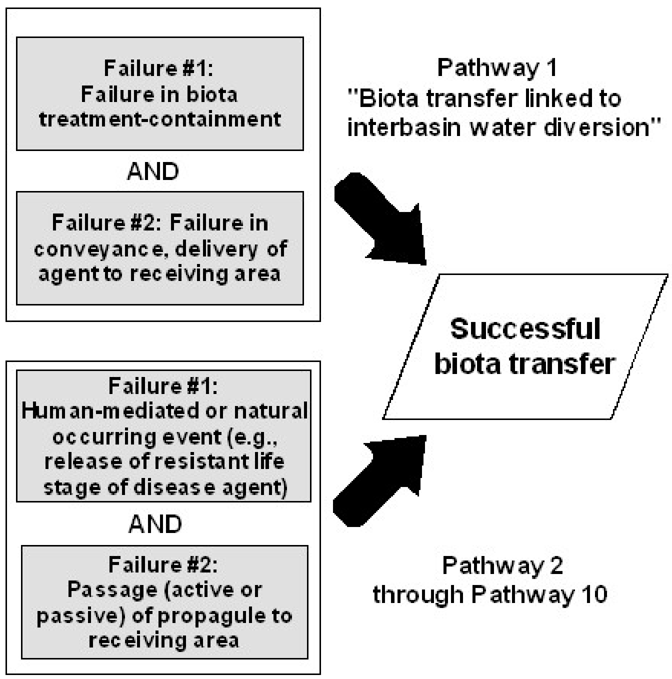

Figure 27. Simple two-step conceptual model used in simulation of competing pathways as factors influencing risks associated with biota transfers.

Input values for Pathway 1, or the "biota transfer linked to water diversion" pathway were based on control system failure probabilities during the system's period of useful life as those were captured by empirical estimates of biota treatment-containment failure and conveyance failure (USGS 2006). This region of the system's life time distribution bath-tub curve was characterized in USGS (2006) in the life time distribution anticipated for control system designed to met performance criteria predicated on regulatory guidance consistent with, e.g., LT2ESWTR, especially those elements of guidance focused on resistant life stages of disease agents such as *Cryptosporidium parvum*. As such, these conditions established an upper bound on acceptable performance of the control system involved in the interbasin water transfer; hence, the pathway characterized by these conditions was a highly managed control system, operating under specified conditions consistent with a "best management practice" implementing a "best available technology" to manage risks. Again, the control system was considered a multiple component system consisting of a water treatment (including containment) and water transmission operation.

In contrast to this highly managed pathway, Pathway 2 through Pathway 10 represented systems having less highly managed, less controlled pathways of biota transfer, each having potentially many failure modes. Again, to assure comparability in simulation outcomes, for this initial simulation the biota transfer process involved in Pathway 2 through Pathway 10 was a two-step series, each step assumed independent of the other. Pathway 2 through Pathway 10 represented systems with transfer modes that ranged from systems being constrained through implementation of surveillance monitoring and early detection and rapid response countermeasures to systems having biota transfer potentially occurring in a largely stochastic manner characterized by high variability linked to multiple random events taking place in a stepwise, yet independent manner. Outcomes of the simulation study are summarized in Figure 28 as percentile plots, and the variance[13] characteristic of the transfer events linked to each pathway is presented in Figure 29. Again, pathways were assumed to operate independent of each other in the simulation. Additionally, Pathway 2 through Pathway 10 were considered independent of interbasin water transfers of Pathway 1that focused on biota transfers linked to interbasin water diversions. When Pathway 1 was assumed not in play—that is, the control system's operation was "perfect" and did not allow biota transfer to occur—only Pathway 2 through Pathway 10 contributed to the biota transfer that would occur as an inevitable event when trials were realized over long periods of time.

Outcomes from the simulation varied with respect to their distribution's properties as indicated by the percentile plots in Figure 28. The distribution for each pathway was unique, yet displayed patterns ranging from normally distributed to lognormally distributed outcomes. Comparison of distribution benchmarks such as percentiles, measures of central tendency, and evaluation of skewness[14] and kurtosis[15] suggested the range of outcomes from the simulation would likely mirror a range of outcomes in the field, and thus provide heuristic tools applicable to informing resource management regarding decisions related to competing pathways that influence risks associated with biota transfers. Summary descriptive statistics characterizing each of the ten pathways are included in Appendix 3. As observation of Figure 28 and Figure 29 suggest, Pathway 1 representing a nominally operating control system presents a relatively

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[13]Variance is a measure of dispersion a probability density function and is computed as the average squared deviation of each number from its mean.

[14]Skewness characterizes the degree of asymmetry of a distribution around its mean. Normal distributions produce a skewness of approximately zero.

[15]Kurtosis characterizes the relative peakedness or flatness of a distribution compared to the normal distribution. Positive kurtosis indicates a relatively peaked distribution, and negative kurtosis indicates a relatively flat distribution. Normal distributions produce a kurtosis of approximately zero.

limited and well defined output characteristic of engineered systems, while a range of variability is captured in Pathway 2 through Pathway 10, a condition not uncommonly observed in variously interrelated stochastic systems.

From an ecological perspective, the interrelationships between systems at-risk and pathways represent a multiple stressor-multiple target exposure that result when pathways linking sources and receiving areas are complete. Regardless of the interbasin water diversions, alternate pathways linking sources with receiving systems will characteristically be less subject to control than alternatives proposed for interbasin water diversions. Depending on the allocation of risks across competing pathways, overall risk of species invasions or shifts in metapopulations associated with water resources may even be reduced, if diversion is implemented with sufficient control systems as part of the design. Water-user needs and water-supplier costs, however, will influence implementation of project specific implementation, and basin-wide water resource management and use will influence competing sources and pathways that go beyond control systems envisioned as part of the NAWS project.

4.0 Risk Characterization and Uncertainty Analysis

This report summarizes a preliminary analysis of risks potentially associated with failures in infrastructure of alternative conceptual designs considered for NAWS and its interbasin water diversions of Missouri River source waters to Souris River basin. Although engineering designs are early in their conceptual development, each of the alternatives includes countermeasures against biota transfers. These risk reduction measures include water treatment options which suggest that infrastructure failure in any of these alternative systems may be linked to interbasin biota transfers. Failures in treatment and containment unit operations, pipes, pumps, valves, motors, or other components of the water transmission system were considered primary elements of this preliminary failure analysis initially developed for RRVWS (USGS 2006), which has been directly imported for NAWS in this analysis. The analysis of risks in Section 3, however, has attendant uncertainties which are considered in the following section along with a characterization of risks. Given the role that uncertainty has in developing a risk management plan, the ongoing NEPA process should be informed of technical data gaps that might influence decisions regarding NAWS.

This technical analysis has been completed in parallel to the that NEPA process and captures a snapshot in the evolving conceptual designs being considered to address the future water needs of the Northwest Area. Four alternatives have been advanced by Reclamation in their DEIS (Reclamation 2007), and each of these alternatives served as control systems considered in this preliminary analysis of infrastructural failure. In a manner consistent with the preliminary risk reduction analysis and failure analysis summarized in USGS (2005b) and USGS (2006), respectively, this preliminary analysis of infrastructural failure considered two general attributes of the transmission system: (1) the spatial attribute, or “where source water will be gained” to address interbasin water diversions linking Missouri River source waters with the Souris River basin, and (2) the implementation attribute, or “how the water will be delivered” to the Souris River basin from Missouri River source.

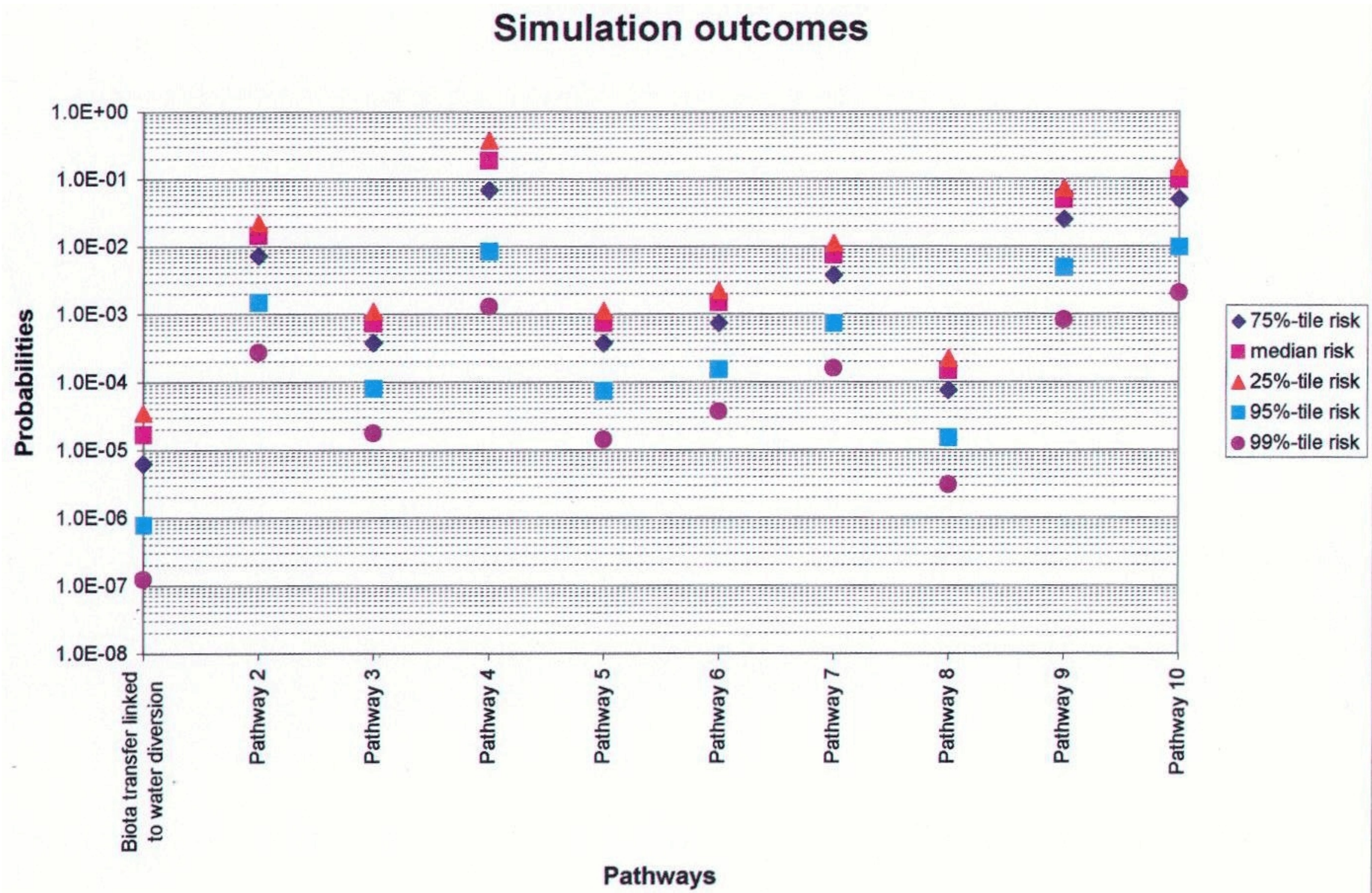


Figure 28. Percentile plots for each of ten pathways included in initial simulation study focused on competing pathways as factors influencing risks of biota transfers.

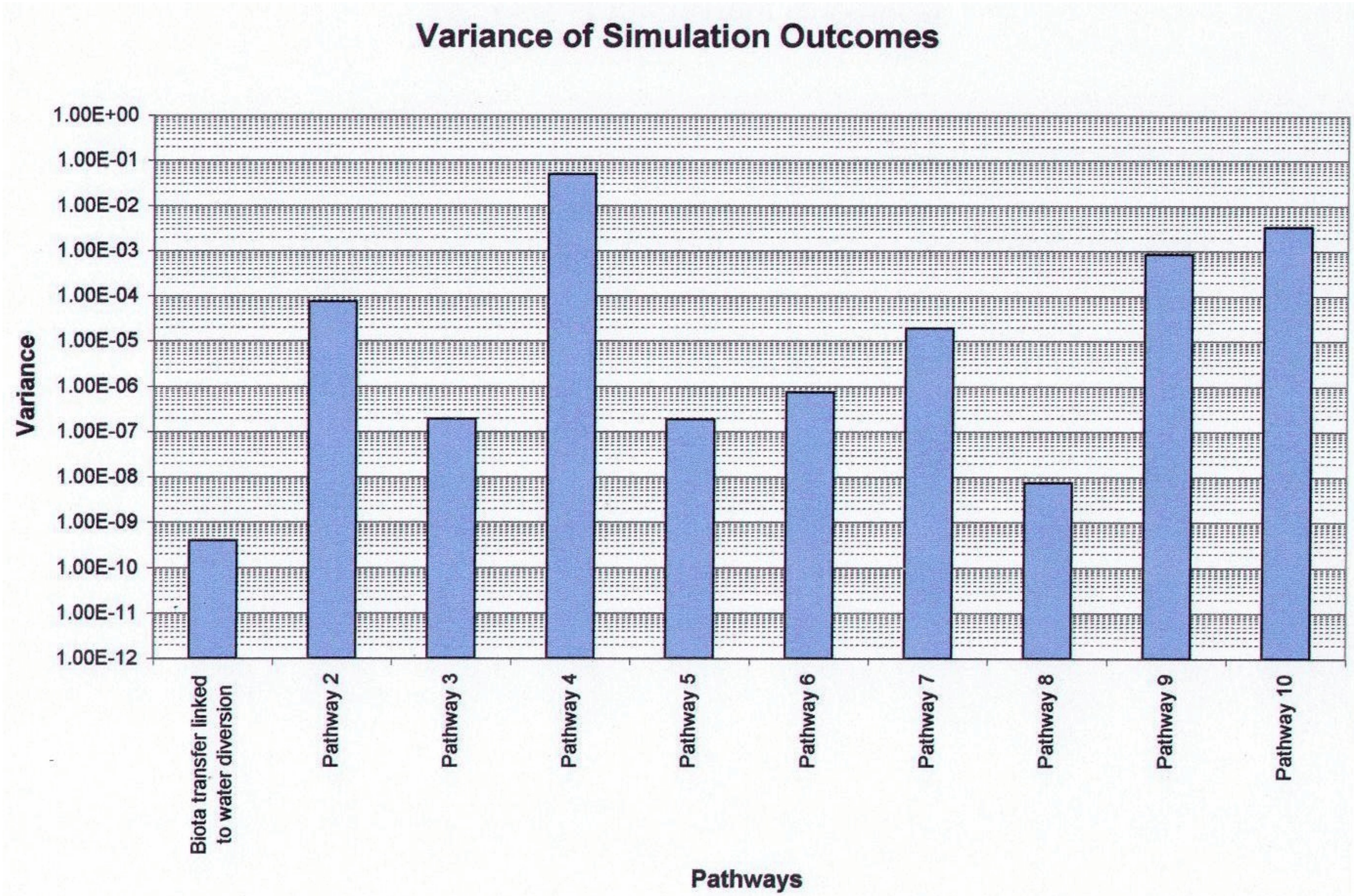


Figure 29. Variances associated with outcomes of the simulation study focused on competing pathways as factors influencing risks of biota transfer.

In contrast to alternatives originally considered for RRVWS project, the four alternatives considered in the DEIS being prepared for NAWS reflect common spatial attributes of water source. Each alternative taps into Missouri River source waters at Lake Sakakawea and relies on available water treatment technologies in their conceptual designs for the control system mediating water transfers from Lake Sakakawea to Minot WTP. Risks related to each of these alternatives is briefly characterized and their associated uncertainties in the following section. For a more complete presentation of alternatives refer to DEIS (Reclamation 2007).

4.1 Risks Associated with Conveyance

The water transmission pipeline connecting Lake Sakakawea and the WTP at Minot, North Dakota is common to all alternatives considered in the NAWS DEIS (Reclamation 2007). While design and construction characteristics linked to biota treatment components of the control system may confer differences in risks characteristic of system failures, the conceptual designs currently considered in the DEIS (Reclamation 2007) suggest that risks linked to water transmission would be common across the four alternatives. From the perspective of a preliminary evaluation of risks, conveyance is relatively non-discriminating among alternatives. Uncertainties associated with one alternative are practically identical to those associated with other alternatives being considered. If water treatment-conveyance dependencies are apparent in future designs developed from these initial set of alternatives, then a reiterative analysis focused on biota transfer risks may be incorporated into future engineering evaluations of alternative(s) of choice.

4.1.1 Risks Associated with Buried pipe. Buried pipe is a common component of the water transmission system characterized in alternatives currently included in the DEIS. In contrast to water transmission pipelines proposed for the RRVWS project, the water transmission components for NAWS are relatively simple and span 45 miles from Lake Sakakawea to Minot WTP where it terminates and melds into existing and future water distribution infrastructure that link communities of the Northwest Area.

Buried pipe brings well-characterized past performance in water transmission and distribution networks. As a result, risks associated with buried pipelines and surface pipelines are relatively well characterized, and risk management practices may be developed within the context of bounded uncertainties (see, e.g., Deb et al. 1995, Gagliardi and Libertore 2000; Moser 2001, American Water Works Service Company 2002, NRC 2005). As was the case for the RRVWS, this past experience and these existing practices benefit the risk management needs of Reclamation and stakeholders sharing a common interest in water transfers and the Red River and Souris River basins of North Dakota.

Buried water transmission is subject to corrosion, soil movements, temperature fluctuations, rainfall, and system stresses in the continuous process of structural deterioration. Failures of buried pipe are linked singly or interactively to a set of potentially interrelated attributes of the transmission and distribution systems and their component parts, as noted in Section 3 (see Table 8 from USGS (2005a), as cited at http://www.structint.com/tekbrefs/

datasheets/buriedpiping/last accessed May 21, 2007). These attributes may be time independent, time dependent, or related to pipe materials independent of the system of which they are part (e.g., DIP has physical attributes that influence its life span independent of its use). Buried pipelines are subject to significant degradation from various internal and external corrosion mechanisms leading to maintenance and repair issues, especially as the transmission system ages. For example, depending on pipe specifications and materials, and the age of the pipe, protective coatings deteriorate (e.g., increasing corrosion risks for DIP) which may eventually lead to leaks or pipe breaks. Such mishaps may occur regardless of the best O&M programs. As standard practice suggests (see, e.g., Moser 2001 and references cited therein), buried pipe of the NAWS transmission pipeline will lie no less than 7-7½ below ground surface (BGS) to prevent freezing. In the northern Great Plains, frost-heaving will be reduced if burial follows guidance available for construction on various soil types (see, e.g., http://www.soils.usda.gov/ technical/handbook/contents/ part618p2.html#29, Andersland Ladanyi 2004, USDA–NRCS 2003), depending on required elevations for pipeline segments throughout the transmission system.

Pipe standards for materials and installation are specified by American Water Works Association (AWWA; see http://www.awwa.org/bookstore/Category.cfm?cat=3 last accessed July 17, 2007), American Society for Testing and Materials (ASTM; see, e.g., http://www.astm.org/cgi-bin/SoftCart.exe/COMMIT/COMMITTEE/C13.htm?L+mystore+jvks6413+1125547345, last accessed May 21, 2007), and American Society of Civil Engineers (ASCE; see, e.g., http://www.asce.org/ instfound/codesandstandards.cfm, last accessed May 21, 2007). For example, water transmission lines must withstand internal and external pressures, including "water hammer" and be resistant to corrosion. Under a variety of specifications, materials for pipeline construction with DIP are designed to handle different pressure loads and rely on region-specific construction techniques that provide a range of flexibility which reduces breaks associated with earth movements such as settling or creep. For a more thorough discussion of general attributes of water transmission and distribution systems refer to Nayyer (2000) and Moser (2001) and standards and references cited therein.

Water management agencies use their transmission and distribution systems to deliver high quality water in the face of breaks, corrosive deterioration, and other forces affecting system integrity. Any of the alternative systems considered in the NAWS DEIS (Reclamation 2007) will be subject to aging. Recently, numerous reports have been published, especially following implementation of the SDWA, which focus on the increasing awareness of aging water transmission and distribution system infrastructure. These studies indicate that regardless of the alternative of choice, water resource managers must have in place a process to assess, plan, locate and repair problems, and update their water transmission and distribution systems periodically. The potential for pipe breaks and the risks that might be associated with subsequent biota transfers are low probability-high consequence events, but should be incorporated into long-term management plans for the water system regardless the alternative selected. Pipeline breaks and their role in evaluating the "life cycle" of a water transmission and distribution network should not be undervalued, particularly given stakeholder concerns related to biota transfer throughout the history of the Garrison Diversion (USGS 2005a). Once an alternative is selected for addressing the water needs of the NAWS service area, engineering designs can go beyond generic industry-wide experience, relying on existing information on pipe breaks (see USGS [2006]), and gather system-specific data that reflects failure rates of systems or system components in order to develop reliability estimates for the system to be built to deliver water to the service area. Life-cycle management of buried pipe should assess the condition of buried pipe throughout the course of the network, manage and mitigate the network's deterioration, and develop safe and cost-effective asset management plans to minimize unexpected outages and minimize long-term costs, be those monetary or primarily non-monetary, e.g., related to collateral events such as biota transfers.

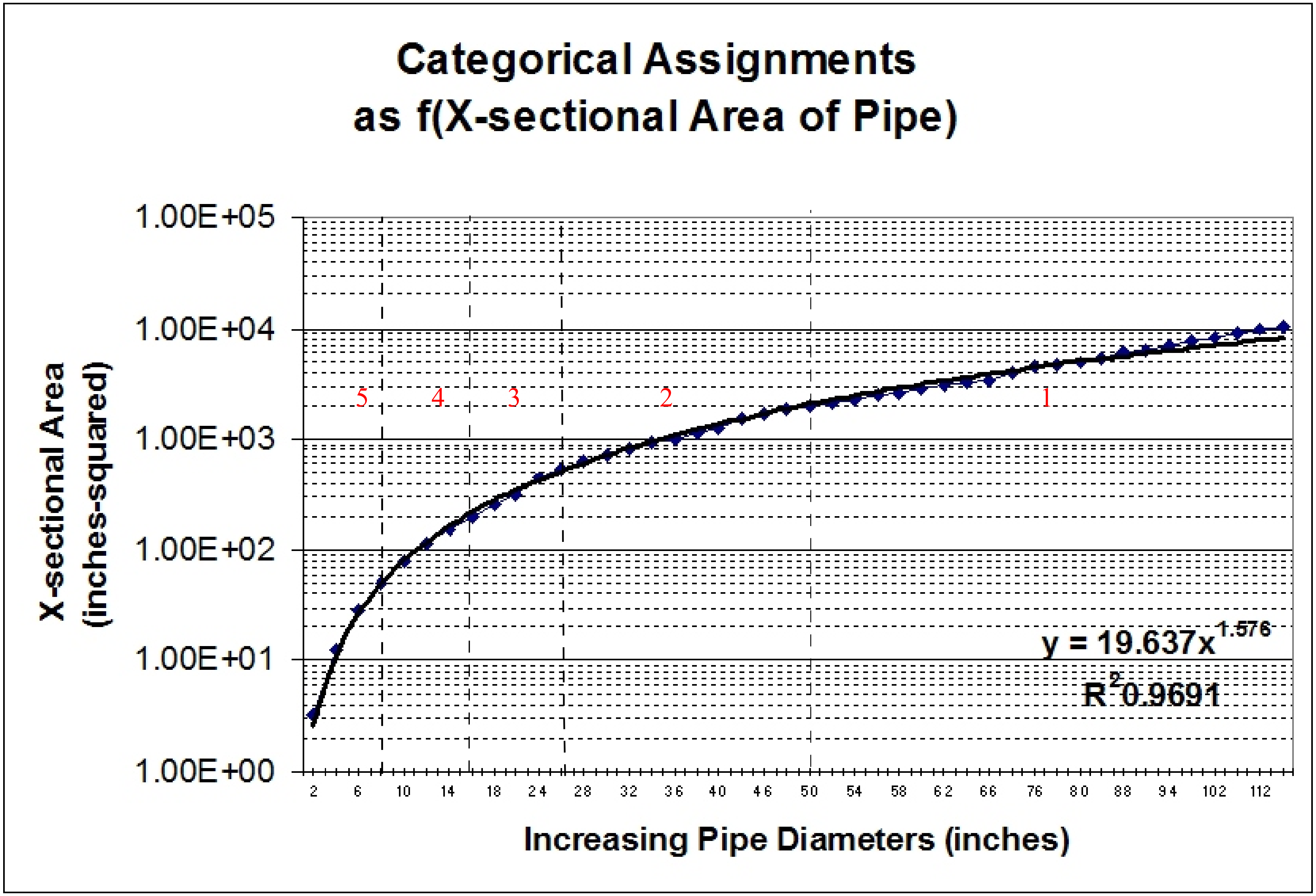
4.1.2 Failures in Conveyance. As captured in USGS (2006), existing data compiled and maintained by industry and government sources suggest failure rates for any of control system presented in DEIS (Reclamation 2007) are readily available for a preliminary analysis. If all parties—governmental decision makers and stakeholders active in the NEPA process—agree on specifications of acceptable risk and risk management strategies to mitigate those risks, empirical data should be sufficient to winnow the list of alternatives for addressing water needs and demands of the NAWS service area.

The following summary presents a brief comparison of alternatives, especially with respect to conceptual design similarities (e.g., water transmission pipeline) and differences, most notably in treatment regimens incorporated into conceptual designs. As in USGS (2005a,b, 2006), engineering costs analysis is not incorporated into these comparison, since those efforts may be better served with a full engineering design.

Risks of Pipeline failure. Reclamation (2007) identified quantities of pipe in the water transmission pipeline currently linking Lake Sakakawea with Minot WTP. Given the relatively limited range in pipe diameters and length of pipeline common to all alternatives, the relationships among pipe diameter, volume of water potentially being conveyed as a function of pipe diameter, and the potential linkages between these interrelated factors and pipe failures, a simple breakout of pipe failure categories discriminates pipeline configurations beyond a simple measure of length (see USGS [2006]; Figure 30). Based on cross-sectional surface area, a simple categorization of pipe diameters was developed, based on statistical properties discussed in USGS (2006). For the water transmission pipeline common to all NAWS alternatives, DIP in 30" and 36" diameter stock material represents relatively large diameter pipe (here, Category 2). Empirical studies and standard references suggest that larger diameter pipe generally tends to have lower breakage rates than smaller diameter pipe (Larock et al. 2000, Mays 1999, Simon and Korom 1997, Tullis 1989). Data on pipe failure has been compiled by government and industry sources. USGS (2006) provided analysis of these data, and observed that DIP presented a median of 6.0 breaks/100 km/year, which is comparable to that for steel pipe (see USGS 2006 for detail).

Given the pipe materials and countermeasures such as cathodic protection incorporated into the pipeline's construction, conveyance risks across for each alternative would be considered low. As noted earlier, selection of alternative of choice will undoubtedly reflect costs and shared specifications of acceptable risks. When the NEPA process has been completed and engineering designs developed, any dependencies between treatment and conveyance should be identified and if sufficient, a reiterative analysis of these risks should be completed.

Figure 30. Evaluation of potential failure-rate differences across a range of pipe diameters (see USGS 2006 for detail).


Categorical Assignments
as f(X-sectional Area of Pipe)
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
X-sectional Area
(inches-squared)
5
4
3
2
1
y = 19.637x1.576
R2 0.9691
2 6 10 14 18 24 28 32 36 40 46 50 54 58 62 66 76 80 88 94 102 112
Increasing Pipe Diameters (inches)

4.2 Treatment of Source Water

Biota treatments included in conceptual designs for control systems posited in each of the four alternatives variously reduce risks of biota transfers potentially associated with water diversions between Missouri River source waters and the receiving system, Souris River basin (see Section 3). However, as noted in USGS (2005a,b, 2006) for technical findings focused on similar issues related to interbasin water delivery to the RRVWS, whether that risk reduction is sufficient to meet stakeholders' risk tolerance remains a risk management decision that is not considered in this technical report. There are no regulatory benchmarks specific to biota transfers nor promulgated standards specifying "acceptable risks" related to species invasions or shifts in metapopulations. Implementing interbasin water transfers in compliance with control systems proposed in the DEIS would bring to resource management discussions a system of control technologies that are risk reduction tools for managing potential biota transfers. While these tools serve to reduce risks—in this case risks related to biota transfers—there are attendant uncertainties that must also be considered.

Work completed in this preliminary failure and consequence analysis anticipate more detailed engineering design and cost analysis, once alternatives of choice have been identified. This report specifically addresses a preliminary analysis of infrastructure failures that may adversely affect water treatment and water transmission functions of the control system envisioned for interbasin transfer of source waters from the Missouri River to receiving areas in the Souris River basin. While the focus of this report lies on events that might enable biota transfers through biota treatment and pipeline failures, other control system failures could reduce invasion risks to practically zero. For example, pump failures associated with water intakes may well disable water delivery, effectively reducing water imports for some period of time. In a time-conditioned analysis, these unintended disruptions in service could reduce risks of biota transfer, since movement of water from one basin to the other might be suspended. Yet, this time-dependent event may foreshadow heightened future risks, given the hydraulic realities of pressure transients and increased risks of pipe bursts in a corrosion-aged water transmission system.

Clearly, the number of scenarios potentially played out in evaluating risks associated with biota transfers realized as collateral events to water diversions from the Missouri River to the Souris River basin far exceeds the specification currently available for the preliminary analyses that follow. The failure analysis that follows, however, provides a level of effort consistent with the intent of the DEIS (Reclamation 2007), which acknowledges the early stage of engineering design. In view of the largely conceptual designs being considered in the DEIS, the failure analysis summarized herein does not identify one alternative as being better than another. Rather, the primary objective of this preliminary failure analysis centers on the role that technical evaluations play in risk assessment process, as noted in USGS (2005a) and other guidance available to the tasks facing natural resource managers (see Section 1, USGS 2005a).

Alternatives are evaluated categorically, consistent with the evaluation of risk reduction characterized in previous reports (USGS 2005b, 2006). Through these categorical rankings, stakeholders and their representative risk managers may be served with technical support that informs their selection of an alternative of choice among those identified in the DEIS (Reclamation 2007).

4.2.1 Failures of Water Treatment Technologies Proposed In Action Alternatives and Their Potential to Reduce Risks Associated With Biota Transfer. Each of the action alternatives identified and characterized in the DEIS have incorporated some biota treatment into preliminary conceptual designs. The primary difference among alternatives is the extent to which treatment is pursed. Each alternative draws water from Lake Sakakawea (see Figures 3 through 5), wherein the flow of events resulting in transfer of source waters to the Souris River basin begins. Earlier in Section 3 as well as in USGS (2005a,b, 2006), a brief background on disinfection and various chemical and physical options currently applied to water treatment requirements pursuant to regulatory requirements, e.g., SDWA and its amendments, was considered. For example, under the regulatory auspices of the SDWA as amended, EPA has regulations that specify minimum acceptable inactivation necessary for public water to be considered potable, including regulations that specify minimum disinfection of (1) 3 log (99.9%) for *G. lamblia* cysts and (2) 4 log (99.99%) for enteric viruses (see Letterman 1999, see also http://www.epa.gov/safewater/sdwa/index.html last accessed May 21, 2007). Water quality characteristics influence disinfection processes, e.g., turbidity and pH strongly affect contact time necessary to achieve target level of disinfection. Microorganisms have varying sensitivities to disinfectants. If an organism has a high resistance to a certain disinfectant, contact time will be greater than that for an organism with a low resistance. Potential selection of resistant forms also varies, e.g., in biofilms formed in the transmission and distribution system.

For NAWS various levels of disinfection can be attained by altering the type and concentration of disinfectant and contact time, or type of physical barrier incorporated into system's design (e.g., microfiltration). Risks of biota transfer may be refined once a disinfection technology has been selected and regulatory and management needs are addressed. Given a specified level of disinfection, biota treatment infrastructure can subsequently be specified to yield the necessary contact time.

Alternative A, Chemical Treatment. As noted in Section 2, Alternative A was originally proposed in the *Environmental Assessment* (Houston Engineering et al. 2001) and *Finding of No Significant Impact* for the NAWS project (Reclamation 2001). As the alternative presenting the least risk reduction potential, the alternative does not yield product water compliant with SDWA, since its initial design criteria focused on biota control achieved solely through disinfection using chlorine-chloramines, where a chloramines residual is maintained in the pipe for biofilm control. Pre-treatment would yield a 3-log inactivation of *Giardia* and 4-log inactivation of viruses prior to crossing the watershed boundary (Houston Engineering et al. 1995). The North Dakota Department of Health had agreed that the pre-treatment facility would achieve the primary disinfection credit required and no primary disinfectant would be required at the treatment plant in Minot (Reclamation 2001). In addition to these treatment countermeasures, several mechanical and structural features and operational procedures were incorporated into this alternative as described in the NAWS Project Biota Transfer Control Measures (Houston Engineering et al. 1998) and the NAWS Project, Biota Transfer Control Measures Update

(Houston Engineering et al. 2001). The final step in this proposed alternative includes final treatment to SDWA standards at an upgraded facility in Minot. The Minot treatment plant currently includes conventional lime softening and would implement ultraviolet radiation for additional disinfection safeguards, if the alternative were selected for implementing the water transfer (Reclamation 2001).

Noting that Alternative A presents least risk reduction, a failure in a control system such as this might present greater likelihood for biota transfer to occur, especially as treatment regimens are not as rigorous as other alternatives under consideration. Although engineering costs may warrant further consideration of this alternative as engineering designs go forward, treatment with chlorine and maintaining residual via chloramine treatment would be a minimum countermeasure against which others are considered.

Alternative B, Basic Treatment. Alternative B includes a coagulation-flocculation-sedimentation basin along with UV disinfection, chlorine disinfection and chloramine residual at the source, with the finishing treatment process remaining at the Minot WTP. This alternative would consist of a pumped flash-mix facility and a partially buried concrete basin for coagulation-flocculation-sedimentation unit operations. Source waters, then, would be treated in a multiple-component system relying initially on conventional pre-treatment followed by UV and chlorine disinfection and chloramination to achieve residue chlorine disinfection (e.g., to decrease biofilm in the transmission pipeline).

As noted for the universal application of conventional pre-treatment practices in alternatives involved with proposed interbasin water transfers for NAWS, UV irradiation and chlorination (including chloramination as a process to assure chlorine residues) are variously included in conceptual designs as a means of disinfection for biota treatment. Provided these biota-transfer countermeasures are equally implemented across alternatives, risks associated with failures in these features of the biota treatment system would be similar across these alternatives. Yet, all alternatives are clearly not equal relative to risks and the role that system failures might play in mediating interbasin biota transfers. For example, in addition to shared countermeasures of conventional pre-treatment regimens, UV irradiation, and chlorination-chloramination, the alternative also incorporates lime softening and microfiltration into the biota treatment regimen that would further reduce risk, once treated source water enters the Minot WTP. In the risk reduction analysis of Section 3, this alternative yielded an intermediate risk reduction score—greater risk reduction than that observed for Alternative A, yet not as great as those scores attained by Alternative C and Alternative D. Depending on risk tolerance of all parties, this level of risk reduction may be sufficient to offset failures that may be linked to the water treatment technologies applied in this alternative.

Alternative C, Dissolved air flotation (DAF) and Media Filtration. As noted in Section 2, Alternative C proposed DAF pre-treatment followed by media filtration immediately prior to a final disinfection. The final disinfection step would include UV irradiation and chlorination with a chloramination process in place to maintain a chlorine residual within the transmission system.

DAF has been used in management of invasive species, e.g., for managing ballast water, where typical body sizes of aquatic nuisance species (ANS) range from 0.02 to 10,000 micrometers. Such a particle-size range would be effective against various microorganisms (e.g., protozoa, dinoflagellates, and bacteria), various planktonic species, plants, insects, other arthropods, worms, mollusks, and vertebrates (see USGS 2005a). For example, bench-scale experiments focused on managing ballast water have demonstrated particle removal efficiencies as high as 98% for a freshwater matrix (see Vong 2002, USGS 2005a,b). Similarly, the New Zealand Ministry of Health (2001; http://www.moh.govt.nz/moh.nsf/c43c7844c94e08cd4c2566d300838b43/5af58e090cf4098bcc25699600754798?OpenDocument, last accessed May 21, 2007) provides guidance for DAF as part of a water treatment system focused on managing risks for drinking water supplies. Their guidance considers coagulation, flocculation and DAF for removing particles (including *Giardia*, *Cryptosporidium*, and similarly sized organisms) and natural organic matter from source waters, suggesting that the combination of water treatment processes could be valuable where low-density particles such as nuisance algae are to be removed. In New Zealand, guidance supporting water management notes that failures within water treatment systems were observed, if coagulation-flocculation-flotation processes did not attain performance criteria (see, e.g., USGS 2005a,b). New Zealand guidance suggests that the coagulation-flocculation-flotation process and their attendant risks should be viewed as part of the treatment process, since performance of that pre-treatment phase of the multiple-component system affected operations that followed in a water treatment series, and subsequently effected outcomes related to increased incidence of disease. The guidance observed that several factors influence the effectiveness of the coagulation-flocculation-flotation process, including the quality of the source water (e.g., waters with little turbidity or of variable quality make good coagulation difficult) and the composition of the organic matter affects coagulant and flocculant type and their dose control (e.g., poor dose control is likely to cause poor floc formation). In summarizing risks associated with DAF used in conjunction with coagulation-flocculation-sedimentation, the event creating the greatest risk involved under performance or failure in the coagulation-flocculation-flotation process that yielded poor removal of particles. The most important preventive measure was assuring that chemical dosing was controlled to match changing raw water quality and quantity. In addition to evaluating risks potentially realized consequent to system failure, a range of countermeasures were presented, e.g., as critical components in routine O&M procedures. In developing their guidance, New Zealand Ministry of Health pursued a HACCP process similar to that previously characterized to foster development of a pre-emptive risk management focused on biota transfers potentially associated with interbasin water diversions (see, e.g., http://www.haccp-nrm.org/ last accessed May 21, 2007; ASTM 2006).

Alternative D, Microfiltration. As noted in Section 2, Reclamation (2007) has provided a full range of alternatives with the inclusion of membrane filtration in Alternative D. Membrane filtration provides a practically absolute barrier to particles and has been granted substantial log removal credit for *Giardia* and *Cryptosporidium* when applied to drinking water applications. A membrane alternative includes a pre-treatment step depending on the type and size of membranes incorporated into the final design. Final treatment at Minot WTP could rely on lime softening capacity currently in place, and no additional plant upgrades would be required.

One factor likely to influence the choice of primary disinfectants, including alternatives involving membrane filtration, would be concerns focused on *Cryptosporidium* or other disinfection-resistant biota that challenge water treatment efforts. Chlorine is insufficient for treating *Cryptosporidium* and other resistant biota, especially once the organisms have encysted. If organisms displaying disinfection-resistant life stages are a primary concern, especially within the context of risks of biota transfer linked to issues related to disinfection of *Cryptosporidium* and other protozoan, bacterial, and viral agents of waterborne disease (see, e.g., Percival et al 2004, White 1999, Letterman 1999, Schippers et al 2004).

Historically, disinfection of pathogenic microbes in drinking water has been largely successful due to chlorination. Yet recently, regulatory agencies have had to make trade offs between the benefits of chlorination and the risks associated with DBPs associated with chlorination processes. For example, early regulatory guidance under the Surface Water Treatment Rule (SWTR) of 1989 mandated inactivation of *Giardia* cysts and enteric viruses and set treatment standards for THMs. Following SWTR guidance, water treatment plants were generally assured of adequate disinfection without exceeding DBP limits. However, recent and on-going studies focused on evaluating human health effects associated with DBPs suggest that SWTR benchmarks for DBPs may present unacceptable risks. Hence, SWTR was amended in 1996 to further lower DBP standards. In addition, an outbreak of cryptosporidiosis in Milwaukee in 1993 and other minor cryptosporidiosis outbreaks have lead regulators to establish a removal requirement for *Cryptosporidium* oöcysts in the 1998 Interim Enhanced Surface Water Treatment Rule (IESWTR). Additional requirements focused on *Cryptosporidium* disinfection were incorporated into the Long-term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) promulgated in January, 2006.

While LT2ESWTR does not directly pertain to the NAWS alternatives (Reclamation 2007), these rules may provide guidance applicable to reducing risks potentially associated with biota transfers. LT2ESWTR applies to water distribution systems of all types and sizes that treat and distribute surface water (or ground water under the direct influence of surface water). The rule's key provisions include:

- source water monitoring for *Cryptosporidium*, including a screening provision for small systems
- increased treatment requirements for systems with high *Cryptosporidium* source water results, and
- covering or treating uncovered finished water storage facilities.

While LT2ESWTR is primarily responsive to public health issues, and in particular to issues related to *Cryptosporidium*, measures compliant with LT2ESWTR may be applicable to addressing design specifications regarding biota transfer issues. For example, systems designed to use particle-size-based countermeasures for source waters containing *Cryptosporidium* would be one technical solution for reducing risks associated with biota of concern identified in Problem Formulation (see Table 2).

4.3 Potential Biological Consequence of Biota Transfers Linked to Control System Failure

Conditioned on the potential linkages between failure of conveyance or treatment modules in the control system mediating NAWS interbasin water transfers, biota of concern may present undesired outcomes, if the breach in biological security presented by the control system yields sustainable populations in the Souris River basin. The brief synoptic summaries of risks and biological consequences associated with biota of concern illustrate the potential adverse effects linked to these unintended biota transfers. Appendix 2 provides greater detail regarding the recent status of the species in the service area and the life history of these representative biota of concern, as needed.

Risk Characterization for Fish diseases and Waterborne Diseases of Terrestrial Vertebrates. Biota of concern included agents linked to diseases of fishes that would potentially emerge as health concerns for the fisheries of the Hudson Bay watershed (Table 2). To complement our analysis of risks associated with causative agents of fish disease, an analysis focused on causative agents of waterborne diseases generally associated with terrestrial wildlife and humans was completed in parallel to that focused on fish diseases.

Fish diseases. While the spectrum of fish diseases far outreaches those species identified as biota of concern in this report (see Noga 1996; Hoffman 1999; Wolf 1988; Roberts and Shepherd 1997; Hoole et al. 2001), *Myxosoma cerebralis*, *Polypodium hydriforme*, *Yersina ruckeri*, and IHNV illustrate the process available to address any number of species that are currently recognized as causative agents of fish disease (in aquaculture or in the wild). As such, these biota of concern contributed to generalized interpretations of risks associated with disease-causing agents that potentially are transferred collaterally in water diversions.

Bacteria, cnidaria, and viruses of fishes. *Myxosoma cerebralis*, as the causative agent of whirling disease in salmonids, is currently a serious disease problem in many states of the western US, including neighboring Montana immediately west of North Dakota. In Montana and throughout the range of the disease in the western US, whirling disease has caused declines in wild trout populations in previously highly productive trout streams such as the Madison River in Montana where nearly 90% of the rainbow trout population has been eradicated by whirling disease. Since its initial record of occurrence in Pennsylvania in 1956, *M. cerebralis* has been isolated and confirmed in disease outbreaks that have occurred in no fewer than 21 states. This greater than 50-year time course suggests the life-history attributes of the disease agent ease the dissemination of the disease, provided primary (sensitive strains of salmonids) and intermediate hosts (*Tubifex tubifex*) occur in the prospective region of distribution expansion. To complicate exposure in field settings, *M. cerebralis* presents highly resistant spores that can survive in the environment for 30 years before, if not immediately ingested by their intermediate host.

In characterizing risks potentially associated with *M. cerebralis* or any disease agent enlisted as biota of concern in this investigation, host distributions (primary and intermediate) are equally critical to the evaluation. Risks of whirling disease must capture two necessary and sufficient conditions before being realized. The intermediate host, *T. tubifex*, is a commonly occurring aquatic oligochete and would likely not limit the spread of whirling disease, if *M. cerebralis* traveled to Souris River basin by means of any pathway. But the occurrence of primary host, a sensitive strain of salmonid such rainbow trout (*O. mykiss* Walbaum) in the areas of concern would strongly influence the extent to which risks of whirling disease were realized. In Minnesota, for example, rainbow trout were introduced and routinely stocked in the state starting in the late 1800s (Eddy and Underhill 1974). Eddy et al. (1972) characterized rainbow trout as "an important sport fish in the cool headwaters of the Clearwater River and streams tributary to Red Lake." Subsequent to their introduction, rainbow trout have been recorded throughout the Red River basin adjacent to the Souris River basin, particularly in the headwaters of the Tongue River and at various locations on the Turtle, Sheyenne, Red Lake, and Clearwater Rivers east of the NAWS service area. Historically, rainbow trout have also been stocked in reaches of the Pelican and Buffalo Rivers (see Peterka and Koel 1996).

Risks associated with interbasin transfers of the causative agent of whirling disease vary across scenarios originally developed in USGS (2005a), but are equally applicable to similar issues in NAWS. The uncertainty associated with outcomes of the analysis suggests that treated water transferred via pipeline would likely reduce risks greatest with lowest uncertainty. The relatively low-risk forecasts for an emergence of whirling disease in the Souris River basin are reinforced by the relatively sparse rainbow trout fishery in the importing region. Unlike those areas of the western US (e.g., Montana and Colorado) where outbreaks have been well characterized and adverse impacts of the disease (including economic impacts associated with declining wild populations of rainbow trout), the receiving system in the Souris River basin of North Dakota has a relatively underdeveloped trout fishery. Risks could be realized if resistant stages of *M. cerbralis* completed a successful transit from Missouri River waters to receiving waters of the Souris River basin after breaching water treatment countermeasures, but the possibility of an event is highly scenario dependent and largely reflects a flow-of-events characterized by their marked stochasticity. For example, source water fully treated in facilities in the Missouri River basin compliant with LT2ESWTR would present negligible risks for transmission of causative agent of whirling disease. Risk estimates for conditions as specified would markedly reduce uncertainties associated with transmission of *M. cerebralis* and other disease agents potentially associated with interbasin water transfers that stem from Missouri River water sources.

Polypodium hydriforme. Although the existing information and available data for this causative agent of fish disease were relatively limited compared to other biota of concern (see Appendix 2), risks associated with *P. hydriforme* potentially transferred collaterally with waters from the Missouri River would be relatively low to very low, depending on the alternative of choice advanced beyond the conceptual designs outlined in Reclamation (2007). Given the existing disease occurrence and a relatively undeveloped monitoring program for the disease (yielding small sample sizes for evaluation), it is unlikely that an outbreak of disease linked to *P. hydriforme* potentially stemming from Missouri River waters could be identified without high uncertainty. Other potential disease agents of concern (e.g., *Icelanochohaptor microcotyle*, *Corallataenia minutia*, *Actheres ambloplitis*, *Ergasilus cyprinaceus*; see Dick et al. 2001) are characterized by uncertainties that exceed those of *P. hydriforme*, and any estimates of risks beyond those forecasts for the parasitic hydrozoan of acipenserid fishes would be largely unsupported by empirical data.

Yersinia ruckeri, the causative agent of enteric redmouth, and infectious hemtopoietic necrosis virus (IHNV) would present similar risks relative to their being collaterally transferred as part of an interbasin water diversion between the Missouri River and Souris River basin. For these biota of concern, risks would vary from low to to very low, again, depending on the alternative of choice advanced to serve water to the NAWS area of interest. Although relatively limited in its characterization, Missouri River Sturgeon Iridovirus, or MRSIV and other fish viruses (see MacConnell et al. 2001) would also present a similar range of risks, although risks across disease agents such as these would inherently vary as a function of host (alternate hosts, as indicated by specific entity) and intermediate host. Even if specified, a particular disease agent is likely to present relatively limited data for a comprehensive analysis of risks focused on a quantitative or probabilistic evaluation, and a qualitative approach may be employed out of necessity.

Waterborne diseases of terrestrial vertebrates (including humans). A range of waterborne diseases frequently expressed by terrestrial and wetland vertebrates, including zoonotic diseases, was considered as part of the evaluation of risks associated with interbasin water transfers. In contrast to most of the disease agents for freshwater fishes considered earlier in this section, each disease agent in this section would not be considered as a potential invasive species, since each currently occurs in Missouri River basin and in Souris River basin. These organisms, however, do serve as representative waterborne disease agents that potentially represent disease agents of terrestrial vertebrates that are potentially subject to outbreaks linked to shifts in metapopulations of these agents in the receiving area. Similarly, although waterborne viruses such as adenovirus, calicivirus, coxsackievirus, and echovirus associated with diseases of terrestrial vertebrates were not considered in detail (see Embrey et al. 2002), the waterborne disease agents considered in connection with fish diseases suggest a range of risks that is captured by these agents targeted on terrestrial hosts.

Bacteria, protozoans, and microsporidia of terrestrial vertebrates. *Cryptosporidium parvum* is a parasitic microsporidian parasite that presently challenges water treatment systems (Embrey et al. 2002), and has received much attention within the context of risk evaluations focused on human health and diseases in other terrestrial vertebrates. Given the basic scenarios considered in this work, the risks of *C. parvum* being transferred from Missouri River basin to Souris River basin in sufficient numbers to document increased disease occurrence in Red River basin ranges from low to very low in water diversions implemented using control technologies within the Missouri River basin that ensure piped waters meeting compliance specifications under SDWA as amended in 1996 and LT2ESWTR.

Giardia lamblia is a parasitic protozoan that remains a public health concern in untreated waters intentionally or coincidentally consumed (e.g., backcountry drinking water sources or ingestion when swimming, respectively) or in treated waters likely to have become contaminated with contaminated materials prior to ingestion. As with other microbiological biota considered in this analysis, risks associated with *G. lamblia* collaterally transferred in interbasin water diversions range from low to very low when water of the Missouri River is piped to distribution systems in the Souris River basin following passage through a serially arranged control system comprised of pre-treatment, treatment (e.g., chloramination) and membrane filtration (e.g., see Schippers et al. 2004).

Commonly encountered waterborne bacteria that have a long history of cause-effect relationships with disease in terrestrial vertebrates were identified as biota of concern by Problem Formulation. *Escherichia coli* has numerous serotypes that currently occur in both Missouri River, and Red River-Souris River basins in North Dakota, Minnesota, and Manitoba, yet it could potentially be transferred in water diversions from the Missouri River to these areas of concern (see Appendix 2). It is highly unlikely, however, that outbreaks of any of various diseases associated with serotypes of *E. coli* could be unequivocally linked to interbasin water transfers. Risks associated with interbasin water transfers under the alternatives advanced for NAWS (Reclamation 2007) are conservatively rated as being low to very low, if implemented via a control system characterized as previously noted for reducing risks associated with microsporidians and viruses. While constructing a control system characterized by serially arranged pre-treatment, treatment, and membrane filtration treatments will likely minimize risks, the feasibility of such as system (e.g., engineering cost analysis) was not included in the analysis of risk reduction tools potentially amenable to the water diversions. From a technical perspective, under the best of circumstances linking Missouri River source waters with shifts in metapopulations expressed as increase disease outbreaks is highly unlikely unless sufficient "fingerprinting" of source waters and waters available to end-users were routinely completed (see Grayman et al. 2001). Regardless of alternative of choice, a monitoring program yielding data sufficient for serotype fingerprinting may be prohibitive as a routine monitoring tool and would depend on water user and stakeholder specifications reflecting their collective risk tolerance.

Risk analysis for *Salmonella* spp. tracks a course similar to that of serotypes of *E. coli*. *Salmonella* spp. (including *S. typhi*, *S. typhmurium*, and other serotypes associated with other waterborne infectious diseases) were considered, not because Reclamation and stakeholders anticipated an outbreak of typhoid fever, but rather these species of enterics present a long history in infectious disease and a rich technical literature with respect their role as sources of waterborne diseases. As biota of concern that capture life history attributes characteristic of other microbial disease agents, *Salmonella* spp. life history and epidemiological characteristics summarized in Appendix 2 illustrate their value as a representative group that has been the object of many risk assessments in the existing literature (see Haas et al. 1999 and citations therein).

For our current application to the characterization of risks potentially associated with interbasin water diversions from the Missouri River to the Souris River basin, these disease agents, as were the serotypes of *E. coli*, are currently cosmopolitan in their distribution; hence, any risks associated with these disease agents would require an analysis of shifts in metapopulations, most likely manifested as disease outbreaks in the importing basin. For alternatives advanced for NAWS, establishing causal linkages between source waters and disease outbreaks in the importing basin may defy attribution, since it is unlikely that outbreaks of any of various diseases associated with *Salmonella* spp. could be unequivocally linked to interbasin water transfers, as would be the case anticipated for serotypes of *E. coli*. The technical requirements for distinguishing sources of a disease agent such as *Salmonella* spp. in drinking water may be a practically intractable problem from an epidemiological perspective unless a monitoring program yielding data sufficient to the effort were in place (see Emde et al. 2001; Grayman et al. 2001). However, if interbasin water diversions were implemented via a control system characterized as previously noted for reducing risks associated with microsporidians and viruses, risks of waterborne disease outbreaks associated with *Salmonella* spp. originating from waters from the Missouri River would be low to very low, depending on which of the NAWS alternatives were selected. For example, as noted for other microbial species enlisted as biota of concern, water diversions mediated by a control system characterized by serially arranged pre-treatment, treatment, and membrane filtration treatments will likely minimize risks, although the capital costs of such an alternative may not be acceptable to stakeholders and decision makers. A complete engineering cost analysis was beyond the scope of this risk analysis, although as alternatives are winnowed, such an effort may be warranted, provided risk reduction is sufficient to allay concerns focused on interbasin biota transfers.

Legionella spp., as most commonly exemplified by *L. pneumoniae*, are ubiquitous and occur in a wide range of freshwater environments (see Fliermans et al. 1981; Hurst et al. 2002). Because of the public health origins of much of the early literature for *L. pneumoniae* (see Hurst et al. 2002), the ecological interactions that lead to the species being included as a member of the current investigation's list of biota of concern are commonly overlooked, which is frequently a shared "case attribute" for instances where low probability events are concerned and investigations are subsequently pursued. As summarized in Appendix 2, a wide range of *Legionellaceae*, including *L. pneumoniae*, are potentially subject to interbasin transfers collateral with water diversions between the Missouri River and Souris River basin. And while not exclusively an attribute unique to *L. pneumoniae*, the role that biofilms play in mediating transfers and influencing risks becomes a more prominent technical issue in the current analysis (see Appendix 2). Biofilms and intracellular parasitism are key factors that bring additional uncertainties to any evaluation of risks characteristic of these relatively recently described microbes (see Storey et al. 2004).

Risks of interbasin transfers of the Legionellaceae, including *L. pneumoniae* and other members of the family are low to very low under a conservative scenario wherein source waters are treated in the Missouri River basin prior to piped transfers to distribution nodes in the Souris River basin. In such a scenario for interbasin water diversion, control systems including mutiple technologies (e.g., conventional pre-treatments with DAF or pressure-driven filtration devices followed by combinations of chemical treatments to maintain chlorine residues) would reduce risks to levels not unlike those for other disease agents included as biota of concern. Under this conservative scenario, this very low risk reflects, in part, our relatively limited technical ability to distinguish between sources of the disease agents (e.g., in the absence of a monitoring program as detailed by Emde et al. 2001).

Cyanobacteria. Cyanobacteria present a significant challenge to water systems throughout North America (see, e.g., Knappe et al. 2004) and the rest of the world (Chorus and Bartram

1999). High-priority biota of concern identified in Problem Formulation included *Anabaena flos-aquae*, *Microcystis aeruginosa*, and *Aphanizomenon flos-aquae*. Each of these species has a long history of causing water quality problems for fish and wildlife (see Wobeser 1997), domestic livestock (see Svrcek and Smith 2004; see also http://www.ext.nodak.edu/extpubs/ansci/animpest/v1136w.htm last accessed May 21, 2007), and public health (Chorus and Bartram 1999). The current analysis of risks clearly indicates that, if conditions amenable to cyanbacterial growth exist within the water distribution system (including storage reservoirs), a margin of safety will be achieved with control systems that incorporate sufficient water treatment technology (e.g., DAF, slow sand filtration, membrane filtration with sufficiently low rejection value) to reduce risks associated with cyanobacteria and their associated toxins.

Risks associated with interbasin transfers of cyanobacteria are relatively low to very low, if scenarios involve multiple technologies to implement interbasin water diversions. For example, slow sand filters and their associated biofilms may contribute significantly to degradation of dissolved organic substances such as cyanotoxins (see Newcombe 2002; Knappe et al. 2004), although for removal of cyanobacteria, water quality (e.g., turbidity) and the biomass of cyanbacteria removed by the slow sand filter likely lead to rapid blocking and decrease the practicability of slow sand filtration (see Chorus and Bartram 1999). Filtration itself may not achieve removal of extracellular toxin, but biological adsorption may lead to decreased cyanotoxin concentrations in multistage treatment systems. For example, bulk cell removal by coagulation and clarification before slow sand filtration may be an effective approach for obtaining the benefits while avoiding rapid fouling (see LeChevallier and Kwok-Keung Au 2004). DAF may also be effective (see Section 3), as are slow sand filtration and rapid sand filtration which have been considered as control measures in water treatment systems, e.g., for treatment of wastewater from fish culture facilities (see Bomo et al. 2004; Bomo et al. 2003; Logsdon et al. 2002; Arndt and Wagner 2004), and pressure-driven technologies are considered highly effective preventive measures to address concerns related to control of *M. cerebralis* propagules (see USGS 2005a, Appendix 10).

Membrane processes, e.g., ultrafiltration (UF), may be effective in the removal of cyanobacteria and intracellular toxins, if membrane rejection properties or adsorption ability for microcystins are sufficient. Generally speaking, molecular cut-off values for most UF membranes would likely not yield removal of soluble toxin, although nanofiltration membranes would be characterized by rejection values yielding reduced risks relative to UF processes. Hence, risks associated with cyanobacteria illustrate the role that subsequent engineering analysis plays in potentially influencing risks potentially associated with interbasin water diversions.

Risks associated with cyanobacteria can be significantly decreased through control system design, yet the source waters may provide conditions sufficient to support cyanobacterial growth. Wherever conditions of temperature, light, and nutrient status are conducive to algal or cyanobacterial growth, surface waters may experience proliferation of these aquatic organisms, frequently as an algal or cyanobacterial "bloom" when the event is dominated by a single (or a few) species. The type of the water transfer system significantly affects the risks associated with cyanobacteria, since problems associated with these biota of concern are likely to increase when ponds and lakes (including water supply reservoirs) are included in the design, especially in areas experiencing eutrophication, e.g., increased population growth with inadequate waste water treatment, and in regions with agricultural practices contributing to nutrient loads to surface waters, e.g., through overfertilization and erosion (see Appendix 2; see also Chorus and Bartram 1999).

Risks to terrestrial vertebrates and to aquatic life are most frequently associated with cyanobacterial toxins in freshwater blooms, and these toxins, e.g., cyclic peptide toxins of the microcystin family, pose a major challenge for the production of safe drinking water from surface waters containing cyanobacteria with these toxins (see Appendix 2). In uncontrolled water storage systems, risks will vary seasonally, since cyanobacteria often dominate the summer phytoplankton and tend to bloom if nutrient conditions exists (e.g., phosphorus is the limiting nutrient controlling the occurrence of cyanobacterial blooms of cyanobacteria, and the lack of nitrate or ammonia favors the dominance of these species, since cyanobacteria tend to be nitrogen fixers). If cyanobacteria are present or dominate at any particular time of the water year, practical problems associated with high cyanobacterial biomass and the potential health threats from their toxins increase. High cyanobacterial biomass may also contribute to aesthetic problems, impair recreational use (due to surface scums and unpleasant odors), and effect the taste of treated drinking water.

Direct cyanobacterial poisoning of animals can occur by two routes: through consumption of cyanobacterial cells from the water or indirectly through consumption of other animals that have themselves fed on cyanobacteria and accumulated cyanotoxins. Cyanotoxins bioaccumulate in common aquatic vertebrates and invertebrates, including fish, mussels and zooplankton. Consequently, there is considerable potential for toxic effects to be transferred through aquatic food chains (see Appendix 2).

Shifts in metapopulations associated with biota transfers associated with water diversions. As noted during Problem Formulation, some of the representative biota of concern were cosmopolitan in distribution and were present throughout the northern Great Plains. These circumstances are illustrated by the current distribution of cyanobacteria and zoonotic disease agents included as high-priority biota of concern. USGS (2005a) had acknowledged the potential for interbasin water diversions to influence existing local populations in Missouri River and Red River basins, which would also be apparent for local populations in the Souris River basin. As in USGS (2005a,b), species invasions are not the issue in this facet of the biota transfer issue, yet mechanistically, the process of dispersal via pathways directly related to proposed water diversions are similar, if not identical, to the initial events characteristic of an invasion that results in an expanded species distribution. Extensive works have been published (see Gilpin and Hanski 1991; Hanski and Gilpin 1997; Hanski 1999; Hanski and Gaggiotti 2004; Beissinger and McCullough 2002) which highlight an increasing focus on populations—microbial, plant, and animal—and the interrelationships among local populations that are mediated by dispersal events across various spatiotemporal scales (see Colbert et al. 2001; Bullock et al. 2002).

Conceptually, Hanski and Gilpin (1997) characterized metapopulations as populations that are spatially structured; that is, there are patches of habitat in which the species can successfully growth and reproduce. From any given species' perspective, much of the landscape serves as an uninhabitable matrix, and the metapopulation consists of an assemblage of local breeding populations linked by movements of individuals, e.g., through migration between local populations. Alteration of local population dynamics and genetics results from these interactions, and as a consequence of the spatiotemporal linkage of metapopulations, local populations have the capacity, e.g., to reestablish themselves following extinction of local populations. Such a characterization of metapopulation leads to the standard definition posited by Hanski and Gilpin (1991) wherein metapopulations are considered as a "system of local populations connected by dispersing individuals" and refines the original term coined by Levins (1969).

From a practical perspective, the technical issues involved in the analysis of altered metapopulation dynamics directly linked to interbasin water transfers consistently outpaced the data available for analysis. Appendix 2 identifies available data and resources capable of collecting data sufficient to the analysis, if future concern warrants the design of monitoring studies to track disease occurrence. As a continuation of our initial foray into the evaluation of risks potentially realized consequent to interbasin water diversions (see USGS 2005a), a range of tools from statistical time-series (see Anderson 1971; Hipel 1985; Chatfield 1995; Kedem and Fokianos 2002) and disease outbreak analysis (see Woodward 1999; Diekmann and Heesterbeek 2000; Kulldorff et al. 2004) were available, but a simple analysis of graphical and summary numeric data (see Appendix 2) was applied to this preliminary evaluation. Provided data are sufficient to more rigorous analyses, such an analysis may be indicated in future iterates of the risk analysis process.

With the exception of data collected under the auspices of public health agencies, the current review of data collections available through public domain are not sufficient for a rigorous statistical analysis required to distinguish between sources of disease agents originating in the Missouri River basin and those originating from the Souris River basin. Even those data collections from public health sources that were available for this effort limited the tools for the analysis. Hence, we opted for a relatively simple assemblage of available occurrence data (see Appendix 2) and a brief narrative interpretation of risks from a technical perspective. In general, our inability to distinguish between sources of disease agents adversely affects our ability to evaluate baseline levels and adequately characterize initial conditions in an analysis wherein projections are required to characterize how past records of disease occurrence (e.g., existing populations and outbreaks associated with disease) relate to future events such as comparisons of disease occurrence "before diversion" *v.* "after diversion." For example, state wide and province wide data available for microbiological, e.g., *Legionella pneumoniae* and Apicomplexa disease agents, e.g., *Cryptospordium parvum* suggest that data are available within-agency to conduct the necessary baseline analysis to evaluate "before diversion" status, although data resolution, e.g., at a county level, does not easily fit into the current investigation's watershed-based analysis. Nonetheless, design of monitoring studies to evaluate "after diversion" condition could be folded into the evaluation process.

Risks and consequences associated sludge disposal. Water quality, including the management of sludge derived from drinking water and wastewater treatment, has a long regulatory history, which would become a factor in analysis of risks associated with sludges derived from source waters delivered to Souris River basin from the Missouri River. Recent focus on sludge (see, e.g., NRC 2002c) would suggest future efforts could be narrowed to technical issues regarding risks associated with biota transfers linked to sludge and biosolids derived from treatment of source waters diverted to Souris River basin from the Missouri River. Sludge is the solid, semisolid, or liquid residue generated during water treatment, and its disposal is regulated under the auspices of the Clean Water Act (CWA). Currently, sludge disposal is generally managed by incineration, landfilling, or disposal at certified surface facilities. Of these alternatives, the practice most likely directly linked to biota transfers would be disposal in upland disposal sites, landfills, and land application.

The use of sludge as soil amendments (soil conditioners or fertilizers) or for land reclamation has increased markedly since 1992[16] in efforts to reduce the volume of sludge that must be landfilled, incinerated, or disposed of at surface sites (see Sopper 1993). Depending on the extent of treatment, sludge may be applied where little exposure of the general public is expected to occur such as on agricultural land, forests, reclamation sites, or on public-contact sites, e.g., parks, golf courses, lawns, and home gardens. Regulations governing land application of sludge were established by US EPA in 1993 in the Code of Federal Regulations, Title 40 (Part 503), under Section 405 (d) of CWA. Sludge conforming to the Part 503 rule standards is termed "biosolids," and under the purview of CWA, biosolids and their management in the US must conform to practices accepted by US EPA as alternatives for handling sludge (e.g., incineration). The Part 503 rule has established management practices for land application of sludge, including concentration limits and loading rates for selected chemicals. Treatment and use requirements placed on sludge are designed to control and reduce pathogens and attraction of disease vectors (e.g., insects or other organisms that can transport pathogens).

While regulations focused on chemicals would necessarily be considered in any future evaluation of risks associated with land application of biosolids, land-application standards for pathogens would likely be the most pertinent to an evaluation of risks associated with biota transfer. Land-application standards for pathogens specified in the Part 503 rule are not risk-based concentration limits for individual pathogens, but are technologically-based requirements aimed at reducing the presence of pathogens and potential exposures to them by treatment or a combination of treatment and use restrictions. Monitoring biosolids is required for indicator organisms (i.e., certain species of organisms serve as indicators for the presence of a larger set of pathogens).

Land application of biosolids is a widely used, practical option for managing the sludge generated at source water treatment plants that otherwise would need to be disposed in landfills or incinerated, then residuals disposed in landfills. There is no documented findings that the Part 503 rule has failed to protect public health; however, additional technical work is required to

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[16]While not directly relevant to issues focus on disposal practices in the northern Great Plains, ocean disposal of wastewater residuals was prohibited in 1992 and drove wastewater management agencies to seek alternative disposal practices strongly reliant on landfills and incineration.

reduce uncertainty about the potential for adverse human health and ecological effects from exposure to biosolids. For example, there have been anecdotal accounts of increased disease occurrence in areas where land-applied biosolids has been completed. To assure the public and to protect public health and the environment, there is a critical need to update the scientific basis of the rule to (1) ensure that the chemical and pathogen standards are supported by current scientific data and risk-assessment methods, (2) demonstrate effective enforcement of the Part 503 rule, and (3) validate the effectiveness of biosolids management practices (NRC 2002c). Risks of biota transfers directly associated with sludge have not been fully characterized given the regulatory framework in place. However, as alternatives are selected, revisiting the management of water treatment residuals may be in order.

4.4 Uncertainties and Risk Management

In the current analysis, a number of uncertainties and assumptions regarding each alternative and risks associated with these alternatives must be incorporated into interpretative context for refining subsequent iterations of risk analysis. While the current analysis of risk reduction acknowledges differences among alternatives posited for NAWS, the summary findings reflect assumptions of risks being identical across systems. Future engineering risk analysis may refine this assumption to capture differences across locations and component parts of the transmission system, e.g., control valves, pipe configurations.

Each of the alternatives involving an interbasin water diversion suggest that reduced risk could be achieved by treatment of intake water at the source and transmission via closed conveyance from Missouri River basin to Souris River basin, a finding consistent with USGS (2005a). However, the extent of risk reduction differs from one alternative to another. To complicate matters, any of the alternatives could be equally foiled by stochastic events yielding a biota transfer–species invasion process. Conceptual engineering options outlined by Reclamation (2007), however, provide starting points for refined engineering analysis of risks and costs, and continued development of detailed designs. If an alternative is selected, or if some alternatives are eliminated and others are moved forward in developing resource management plans, then a framework for evaluating the condition of water system components and developing O&M schedules should be included in long-term management plans, if risks of interbasin biota transfer are to be minimized. These project management needs related to projected long-term use require an evaluation of uncertainties captured by the current alternatives, which is the primary focus of this section and brings closure of this investigation.

Risk reduction and control systems technology. The analysis of species invasions or shifts in metapopulations associated with interbasin water diversions should be incorporated into risk management activities, including reiterative evaluations of control system technologies potentially serving to reduce risks associated with interbasin water diversions. The current investigation has focused on competing risks, e.g., as those are reflected in project and nonproject pathways, and a similar analysis could be fully developed to evaluate risks associated with the range of mitigation options available to the design and implementation of control systems serving water diversion needs. Classical competing risks approaches could be applied to the analysis of water treatment options as those related to risk reduction.

For example, chlorination of drinking water supplies as a standard disinfection tool has a relatively long history and has greatly decreased mortality from waterborne infectious disease in the 20th century (see http://www.awwa.org/Advocacy/learn/info/HistoryofDrinkingWater.cfm last accessed May 21, 2007). However, adverse effects associated with various chlorination practices have been identified that suggest an unintended competing risk process has been ongoing since chlorination became a tool common to water treatment technologies. As noted earlier, finished water resulting from chlorination contains DBPs, which are increasingly chemical constituents of concern. From a competing risk perspective, the benefits of water disinfection to manage risks associated with biota transfers must be considered within the context of these process-derived constituents presenting potentially adverse effects on the water consumer; that is, these competing risks must be considered to gain the benefits of water disinfection while minimizing the potential for chemical-related adverse effects associated with disinfection. For example, risks associated with exposure to DBPs varies across the range of DBPs, the source of water, and time of year which influence the presence and relative concentrations of these chemicals. The reader is referred to USGS (2005a,b) for greater detail regarding specific DPBs that are potentially the focus of reiterative analysis targeted on competing risks associated with water treatment.

Uncertainty related to system failures and biota transfer. While uncertainty was considered in some detail in USGS (2005a,b, 2006), a wide range of sources may be referenced for more comprehensive understanding uncertainty as that relates to environmental and engineering decisions (see, e.g., Ayyub 1998, Halpern 2003, Hammond 1996, Jordaan 2005, Kahneman et al. 1982, Morgan and Henrion 1990, Parsons 2001, Tung and Yen 2005). While a detailed consideration of engineering uncertainty may be incorporated into future analysis linked to selection of alternative of choice, in general, two forms of uncertainty influence the interpretive context for the current investigation.

Aleatory uncertainty—often referred to as random uncertainty or stochastic uncertainty—deals with the predictability of an event. In contrast, epistemic uncertainty—also called subjective uncertainty, parameter uncertainty, or state-of-knowledge uncertainty—deals with our state-of-knowledge about a model or portions of a model used in the analysis. Epistemic uncertainty includes both parameter-specific uncertainty and model-specific uncertainty, which are simply different levels of uncertainty embodied within a model. The current discussion of uncertainty will reflect a primary focus on aleatory uncertainty, given its presumptively primary role in mediating failure events that might yield the initial steps in a biota transfer yielding a successful species invasion or shift in metapopulations. Although epistemic uncertainty should be fully incorporated into engineering designs as needed, conclusions reached in this or any other analysis will continually be challenged by our state-of-knowledge, which must be considered within the context of acceptable risk. Similarly, unlikely stochastic events, e.g., occurrence of earthquakes potentially yielding infrastructure failures, may not be a primary concern of risk managers, given the prevailing engineering standards and practices in areas of the northern Great Plains of Minnesota, North Dakota, and Manitoba, but interactions between stochastic events and any engineering structures should also be also considered within the context of acceptable risks.

In this section, uncertainties captured in the current investigation are considered in two interrelated collections, one reflected by the inherent uncertainties of the conceptual designs presented in the DEIS for NAWS (Reclamation 2007) and the other related to the materials and installation of infrastructure incorporated into those conceptual designs. The former collection of uncertainties are conveniently viewed through the lifetime distribution curve, which potentially displays system failures that deviate from the traditional bath-tub curve. Not only should design engineers be wary of these uncertainties in lifetime distributions that influence, e.g., development of O&M schedules, but stakeholders must be cognizant of limitations in the engineering process that may be entangled with long-term support of infrastructure, e.g., financial support earmarked for O&M activities.

Uncertainty associated with traditional concepts of the bath-tub curve. As noted in Section 3, the bath-tub curve ideally portrays system failure through its lifetime, wherein early failure rate of a system is relatively high during system initiation followed by a period characterized by a relatively constant failure rate, which subsequently increases late in the system's life cycle. Recall that system reliability may simply be viewed as the reciprocal of failure; hence, system reliability will decrease with age, if it follows the conventional system process. Mean Time Between Failure (MTBF) is a frequently applied metric in engineering, especially with respect to discrete components, e.g., motors, pumps, and valves, as well as overall systems such as those multiple-component designs.

MTBF considers a system renewed after each failure, then returned to service immediately after failure. For typical distributions characterized by some variance, MTBF only represents a top-level statistic and may not be suitable for predicting detailed time of failure, as uncertainty in failure distributions are inherently variable as a function of time. Simply defined then, MTBF is the average time between failures, and in the present investigation was based on historical data available from existing data compilations or estimated by vendors based on industry experience. Regardless of its data source, MTBF is regarded as a benchmark for reliability, since the measure considered over time can readily identify components or systems that deviate from the value, e.g., present failure rates exceeding MTBF, and appropriate action taken. Where MTBF breaks down is when MTBF estimates are applied without sufficient design specification to identify existing data most pertinent to the estimation process, especially when complex systems are being considered.

While failure estimates derived from USGS (2006) and applied in the current analysis are sufficient for a preliminary investigation, once full engineering designs are developed, refined estimates of failure rates should be identified and system failures re-evaluated given these focused, empirically-based inputs (e.g., failure rates for specific pumps may be applied to analysis, or specific pipe materials may be incorporated into the analysis, following their design specification). Additionally, depending on final engineering designs, fault-tolerance will be more fully characterized. Specifications of component or system reliability will be better supported by existing data, although fault-tolerant systems tend to be increasingly more complex than non-fault-tolerant systems (see, e.g., Puccia and Levins 1985, Barlow 1998, Blischke and Parbhakar Murthy 2000, Bloom 2006, Cox and Tait 1998, Falk et al. 2006, O'Connor 2002, Rausand and Høyland 2004, Tung et al. 2006). Increased levels of system complexity generally require long-term planning be sufficient with respect to O&M schedules. System malfunctions may result from one major failure, but may be caused by unexpected interactions involving failures of multiple components, e.g., complex systems whose components are tightly integrated typically fail through the culmination of multiple components failing and interacting in unexpected ways. For example, several component failures—none independently disabling—may interact in unpredictable ways that, when combined, cause system shut malfunction, in part because of the manner in which complex, interactive systems nominally function. Undetected errors in system function (failures that are not observed, e.g., leaks not detected in transmission piping or bearings wear internally with pumps) may occur. Failures may be readily observed or latent. Latent failures or incipient failures are more difficult to identify and repair. As control systems enter the full design phase of project development, engineering decisions regarding the level of system complexity required, e.g., to increase fault tolerance, will undoubtedly become an increasingly critical issue of ongoing discussions. Increasing control system complexity, however, does not necessarily imply an increase in a system's integrity throughout its in-service lifetime, and relatively simple water transmission networks may be sufficient to project needs. Complex engineering systems tend to be variously coupled. The level of system development for water withdrawal, treatment, and transmission system may be relatively simple, and engineering controls may be developed in direct response to system complexity. Depending on final engineering design for alternative of choice, the level of system complexity (e.g., built-in redundancies to assure system failures are minimized) will undoubtedly reflect uncertainties and their role in maintaining system integrity. Once decisions regarding alternatives of choice are reached, general discussions of system complexity and its role in guiding full designs can be pursued (see, e.g., NRC (2005a), Mays (2005), and Mays (1999) for supplemental background).

Within the context of uncertainty and system performance, risk management practices must be in place, because all systems fail. A system's fault tolerance may lead to a false sense of system security, since chances of system failure may be very small at any particular moment, and perceptions of risks will be influenced by differences in an individual's or group's interpretation of categorical or numerical estimates (Miller and Lessard 2000, Morgan and Henrion 1990, Nott 2006, O'Brien 2001, Perrow 1999, Rustem and Howe 2002, Sustein 2002). Equally important are the roles that time and system complexity may play in managing risks. For example, even in the simplest system, time-in-service or other measures of system aging will influence system performance through time; hence, risks of failure are dynamic. Also, as a system's complexity increases, the interdependency of component parts likely increases, which may lead to nonlinear behavior and increased risks of system failures. Risk managers must face a range of scenarios, all linked to the recurring question: "When the system fails, how easy will it be to recover?" For highly fault-tolerant systems, likelihood of failure is less that for a system lacking redundancy—when they do fail, they can be problematic with respect to their restoration to nominal function. Designed fault tolerance may be built in the system, if components critical to meeting performance criteria, e.g., maintaining biota treatment at prescribed levels of disinfection or removal, are identified, and system down-time that would adversely affect delivery of product water could be reduced.

Although widely applied and having a long history in reliability analysis, MTBF should be considered within the context of its inherent shortcomings relative to uncertainty. Component MTBFs are compiled in databases that are heterogeneous collections of failure data (e.g., across many different manufacturers, components with similar functions but having different designs and performance specifications), which contribute to inaccuracies and widely divergent values that are poorly captured by estimates of central tendency. In part, reliance on MTBF has led to the negative exponential distribution being applied frequently to failure analysis, which may yield an unknown bias to forecasts projected for a typical lifetime distribution. Once engineering systems are more fully designed, however, these shortcomings may be addressed, and uncertainty should be less than experienced in preliminary analysis.

While MTBF has been increasingly considered an "acceptable" level of failure, often linked to identifying root-cause of a failure, such engineering practice is being reconsidered through alternative measures, e.g., Maintenance Free Operating Period (MFOP), that are being developed (see, e.g., Kumar et al. 2000, Todinov 2005). While these measures are currently not fully supported in all engineering practices, depending on the project's timeline, these alternatives may be applicable to alternatives advanced to full design.

Lifetime distribution and hazard function. MTBF assumes that the failure rate is constant for all intervals, yet the failure rate of a system more likely varies with time. By calculating the failure rate for smaller and smaller intervals of time, Δt, the interval becomes infinitely small and yields a hazard function which is the instantaneous failure rate at any point in time,

$$h(t) = \lim_{\triangle t \to 0} \frac{R(t) - R(t + \triangle t)}{\triangle t \cdot R(t)}$$

or,

$$h(t) = \frac{f(t)}{R(t)} \quad .$$

If the hazard function is constant, then the failure rate is the same for any equal period of time, which implies that failures occur with equal frequency during any equal period of time. While the exponential failure distribution has a constant failure rate, the Weibull distribution may be characterized by a hazard function that is not constant, but varies with time (see USGS [2006] for detailed consideration of distribution assumptions). Regardless of which distribution is incorporated into any preliminary analysis, uncertainties in any forecasts will be unavoidable.

A life distribution is simply a collection of time-to-failure data, or life data, graphically presented as a plot of the number of failures versus time. Failure data compiled through existing data sources are similar to any statistical distribution, but input values are life data that are necessarily time dependent. Data quality and quantity issues are not unlike those encountered in analyses developed from data mining activities, e.g., Bessler et al. (2001), Dansu and Johnson (2003), Vazirgiannis et al. (2003).

The typical bath-tub curve considers all possible failure mechanisms that the population will encounter. Some failure mechanisms may occur more frequently in the early life phase, while others will be more common in the steady-state or wear-out phases. Most often, life distributions are characterized by the normal distribution, the exponential distribution, the lognormal distribution, or the Weibull distribution. Different failure mechanisms will yield time-to-failure data that fit different life distributions, which should be reiterated from this preliminary analysis, once system design is fully specified. As a source of uncertainty in the current analysis, selection of life distribution may be addressed in a sensitivity analysis that must be developed under specification of a full system design. Forecasts in the current study were based on Weibull analysis completed in USGS (2006), with early failure phase essentially pacing a negative exponential. Assumptions of other life distributions may be employed by stakeholders as they consider various alternatives currently envisioned in the DEIS (Reclamation 2007). Again, the reader is referred to USGS (2006) for expanded discussion of uncertainties related to alternative lifetime distributions.

Alternative lifetime distributions. Simply stated, reliability is the probability of a component or system performing as intended for some period of time under specified operating conditions. Typically, reliability is graphically captured by the bath-tub curve (see Section 3), yet ample observation suggests the typical distribution need not always be characteristic of all systems. For example, alternative estimates of failure rate functions may indicate life distributions far from the typical bath-tub curve (Figure 31 and Figure 32). Depending on the system, its design and build, both figures illustrate lifetime distributions potentially observed, e.g., for an interbasin water withdrawal, treatment, and transmission system. Figure 31 and Figure 32 both present a decreasing failure rate early in life largely linked to the start up process (e.g., handling or installation defects), then each characteristically presents a constant failure rate reflecting the system’s inherent reliability. But, each hypothetical system then enters the transition to wear-out phase differently, e.g., because of differences in O&M practices. Figure 31 displays increasing failure rate as the system enters wear-out, then returns to a decreasing failure rate associated with, e.g., a delayed maintanence operation or repair necessitated by component failure.

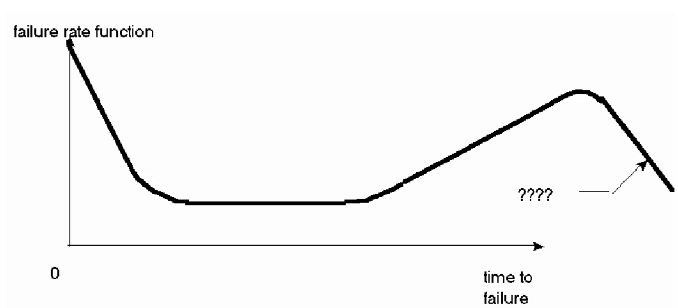

Figure 31. The bath-tub curve with typical wear-out phase, e.g., displayed in systems having delayed maintenance schedules (from L. George, American Society for Quality at http://www.asq.org/).

In contrast, a similar early-life and steady-state (constant failure rate) period may be displayed by a system, as illustrated in Figure 32, but because of differences in maintenance practices (e.g., regular maintenance schedule *v.* condition-based maintenance practices) failure rates do not enter the typical wear-out phase of system life, e.g., failure rates do not increase or ideally, continue to decrease with time.

Both failure rate functions depicted in Figure 31 and Figure 32 illustrate the value of component retirement in maintaining system performance, where the system in Figure 31 experiences decreased performance owing to delayed retirement, and the system in Figure 32 experiences enhanced performance linked to retirement prior to initiation of wear-out phase. Depending on engineering and risk management practices that support the system of interest, either lifetime distribution may be acceptable, e.g., early retirement means fewer operating hours per component per time which will have an associated unit cost. In contrast, retirement initiated upon observation of increased failures in the system may be acceptable, given the risk tolerance specified for the system.

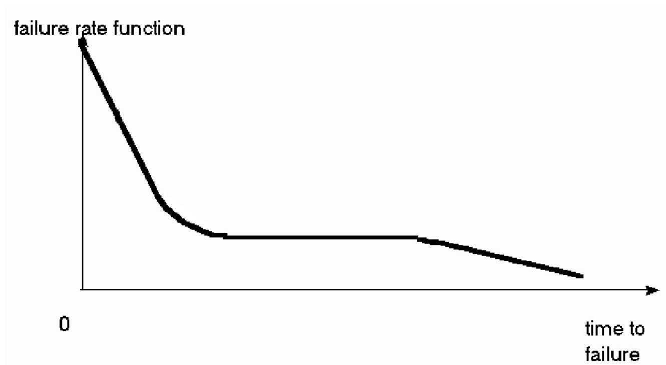

Figure 32. Typical bath-tub wear-out phase is not observed because repair and replacement schedules include retirement prior to increased failure rates characteristic of wear-out phase (from L. George, American Society for Quality at http://www.asq.org/).

While these are but two of the possible alternatives potentially associated with a control system comprised of modules targeted on system functions—water withdrawal, water treatment, and water transmission—the preliminary failure analysis of Section 3 includes an outcome typical of a non-repairable system, which in part reflects the conservatism reflected by stakeholder concerns. Rather than enter a reiterative analysis based on conceptual designs captured in the DEIS (Reclamation 2007), stakeholders working with Reclamation can evaluate alternatives collaboratively, as the NEPA process unfolds in the near and distant future.

Uncertainties associated with control system, its infrastructure materials and installation. While numerous components will necessarily be specified and incorporated into a control system as a full design matures, for this preliminary failure analysis the greatest uncertainties are captured by the system and its components—water treatment and transmission modules—most likely critical to mediating biota release in the event of failure. Narrative discussions of uncertainties associated with conceptual system designs identified in the DEIS

(Reclamation 2007) and their interactions with environments (internal and external) that would influence their performance will be considered in the following sections.

Uncertainties associated with control system. The preliminary failure analysis for the conceptual engineering designs identified in DEIS (Reclamation 2007) relied on a single presumptive lifetime distribution for the control system (see Section 3; see also USGS [2006]). That lifetime distribution also reflected random system behaviors bounded by empirical limits suggested from government and industry data compilations or conceptual limits linked to presumptive regulatory values generalized, e.g., as extensions to benchmarks included in LT2ESWTR for protection from disinfectant resistant organisms such as *Cryptosporidium* spp. (see USGS 2005a, particularly Appendix 10 correspondence with Whirling Disease Foundation regarding efficacy of microfiltration in controlling *M. cerebralis* life stages mostly likely to occur in fish hatchery discharges). Hence, a presumptive bound to system performance may rely on benchmark values linked directly to public health concern yet confer sufficient margin of safety for concerns related to fish and wildlife health.

Alternative lifetime distributions are potentially of interest to stakeholders and should be considered when full design specification is available to, e.g., develop a reliability-based maintenance program. Beyond the issue of presumptive lifetime distribution, even relatively simple systems present a range of uncertainties, which stem from performance of system components as well as interactions among components. System attributes manifested by component interactions in and of themselves may contribute to system failure, or perhaps serve as a primary factor leading to a system's loss of integrity and failure to perform as intended. Because system failure potentially involves factors linked to interaction among components as well as the components themselves, uncertainty associated with systems go beyond a simple analysis of individual components. Hence, a preliminary analysis of system failure and the role failure potentially plays in biota transfers must rely on tools such as root-cause analysis and failure-mode and effects analysis (FMEA). Given relatively simple conceptual designs in Reclamation (2007), a fully implemented application of these tools in the current investigation would have been premature. Yet, these tools should be incorporated into future analyses where FMEA completed within a HACCP process may help refine failure analysis in parallel with future engineering designs. FMEA is a flexible tool, easily imported into a HACCP process, and has been variously adapted for many different purposes. For example, countermeasures associated with control systems (e.g., pressure relief valves, pipeline infrastructure, etc. intended to offset pressure transients and flows) would serve as offsets linked to reducing risks associated with pipeline failures experienced consequent to water transmission in a closed conveyance. Please refer to USGS (2006) for a detailed discussion of FMEA and root-cause analysis as tools to address uncertainties related to water treatment and transmission systems.

Uncertainties captured by biota treatment and water transmission pipeline. As noted in Section 3, water withdrawal, treatment, and transmission systems involve a variety of modules. Each of these modules or components may be further divided into components and sub-components, all capable of failure independent of one another or as a result of a failure linked to their interaction (see, e.g., Cesario 1995 , Griggs 2005). For example, pumping stations consist of structural, electrical, piping, and pumping unit sub-components, with the pumping unit further sub-divided into pump, driver, controls, and power transmission units. Characterization of sub-components varies on the level of detail required for analysis as well as the level of detail of available data, which will ideally match the hierarchy of building blocks used to construct the water withdrawal, treatment, and transmission system. As such, uncertainties associated with these system components influence this preliminary failure analysis, and set the agenda for the reiterative approach practiced in risk analysis.

For example, a water transmission system operates as a system of independent components with the hydraulics of each component being relatively straightforward, e.g., fluid flow through pipes. However, these components depend directly upon each other and influence each other's performance, including interactions that may yield a fault that results in system failure. Uncertainties associated with this aspect of the preliminary failure analysis should be easily addressed, as the initial set of conceptual designs is winnowed and subsequently developed in a detailed engineering design and analysis. Then, the preliminary failure analysis can be refined through reiteration to include, not only greater detail of components, but also an evaluation of how the systems will perform hydraulically under various demands and operating conditions. A fully integrated hydraulic analysis of a full-design system, including water withdrawal, treatment, and transmission components, will be capable of greater resolution in forecasting system failures related to, e.g., pipe breaks, leakage, valve failure, and pump failure (see, e.g., Mays 1989, 2000, 2002, 2004a).

Water treatment is a critical function of the system envisioned in Reclamation (2007). As noted in USGS (2005b, 2006) and throughout the water resource's literature (see, e.g., Haas 1999 and references cited therein), water disinfection—whether targeted by conventional public-health related concerns associated with drinking water or targeted on concerns related to risks associated with biota transfers consequent to interbasin water diversions—generally occurs as a two-step process wherein (1) particulate matter is removed by conventional treatment to reduce turbidity in source waters and thus, reduce "habitat" for viruses and bacteria adsorbed to particulate material, and then (2) pathogenic microorganisms are inactivated by chemical treatments (such as chlorination and chloramination), physicochemical treatments (such as UV disinfection), or removed through physical treatments (such as membrane filtration; see, e.g., Letterman 1999 for overview of water treatment process; see also Mallevialle et al 1996, Duranceau 2001, Schippers et al 2004 for discussions of membrane systems). Combined water treatment technologies may be applied to the water disinfection process, although each step in the water treatment process will be characterized by uncertainties. In this preliminary failure analysis these uncertainties are linked to estimates of performance benchmarked on available regulatory guidance, which assumes those indicators sufficiently attend to uncertainties reflected by biota transfer issues.

For example, target organisms such as *Cryptosporidium* spp. served as preliminary indicators of system performance and provided initial support in an analysis focused on wider concerns related to biota transfer. For disinfection-resistant agents such as *Cryptosporidium* spp. and similar sized organisms, filtration provides an alternative method of treatment through removal, which may be used singly or in conjunction with other treatment technologies (see, e.g., Schippers et al 2004, Duranceau 2001, Mallevialle et al 1996). Similarly, UV irradiation may provide sufficient inactivation to satisfy water treatment objectives, since treatment may not be sufficient to address risks associated with chlorine-resistant life stages. Adequate filtration or alternative treatments may attain those performance criteria and provide protection from organisms whose life histories suggest such treatment methods would be capable of achieving the level of disinfection or inactivation specified. The strength of combined disinfection and inactivation technologies may provide treatment of, e.g., *Cryptosporidium* and other protozoan, bacterial, and viral agents of waterborne disease sufficient to meet stakeholder concerns related to biota transfer (see, e.g., Percival et al 2004, White 1999, Letterman 1999, Schippers et al 2004). Both UV disinfection and membrane filtration have been incorporated into conceptual designs considered in the DEIS (Recalamtion 2007), and once the final list of full-design systems has been identified, uncertainties associated with these treatment technologies may be more completely characterized.

Regardless of the water treatment modules configuration in a full design, water transported through the transmission system will not be sterile; hence, even in the final engineering design, uncertainties will be present that will necessarily influence how system failure will be perceived relative to its role in achieving biota transfer. Although treated waters will be relatively free of organisms, product water entering the transmission module from the water treatment module may contain organisms that survive the treatment process (e.g., recovering from UV treatment will occur, body size was less than size exclusion limit, or short-circuiting occurred in an otherwise normally functioning membrane unit; see Schippers et al. 2004). Also, organisms may enter the transmission system through the pipe network, a circumstance more likely to occur with system aging. A variety of pathways are available to organisms and enable their entry into the water transmission system following treatment, including treatment breakthrough or short-circuiting, leaking pipes, valves, joints, and seals, recolonization of water storage reservoirs, and inadequate system security among others. A steady, although intended to be low, influx of bacteria, fungi, protozoa, algae, nematodes, and other microorganisms may enter any transmission and distribution system (Sibille et al., 1998), and their origins may be through the source water (even though it has passed through a biota treatment module) or at any point within the transmission system following output from the treatment unit. Treated water encounters numerous possibilities for recontamination, e.g., based on the system's construction, operation, and maintenance (see, e.g., Berger et al. 1993, EPA 2004d, AWWA 2006a). Consequently, regardless of their source, these organisms will enter the transmission system, attach to pipe walls, and become part of a biofilm (see, e.g., LeChevallier 1999, Berger et al. 1993), which is a complex mixture of organisms, organic, and inorganic material accumulated within a microbial-produced organic matrix attached to the inner surface of piping, generally as patchy accumulations whose establishment initially reflects hydraulic "habitats" amenable to colonization (see, e.g., van der Wende and Characklis 1990, Abernathy and Camper 1997, LeChevallier 1999a, Doggett 2000).

Other sources of uncertainty related to colonization of the transmission system are numerous. For example, regrowth events may occur, e.g., any growth that occurs in the water-system network, most often as a result of recovery and growth of environmentally- or disinfectant-stressed microorganisms. An organism's survival in water transmission and distribution systems varies with their ability to grow and produce biofilms. These organisms will range in their pathogenicity, and include biota of concern as well as numerous species that present similar life histories. Formation of biofilms may increase pipe corrosion, and MIC—microbially-induced corrosion—may adversely affect pipe hydraulics and reduce water quality through increased microbial populations within biofilms. Broad classes of organisms and toxins, including viruses, bacteria, fungi, protozoa, invertebrates, algae and algal toxins, and microbial toxins, are potentially of concern and should be considered within the context of system failures upon reiterative analysis completed as detailed engineering specifications are available. For a more complete treatment of sources of uncertainty linked to microbial communities and biofilms as sources of biota transfers potentially viewed as derivatives of system failure see, e.g., Marshall 1992, LeChevallier 1999a.

Uncertainties associated with infrastructure materials and installation. Given conceptual designs for NAWS, (Reclamation 2007), construction of transmission pipeline is practically complete. DIP has a long history in its role in water transmission and distribution systems, and is well characterized with respect to its capacity, e.g., to handle different pressure loads throughout its lifetime. For buried pipe, gasketed joints are commonly used in pipeline construction and provide a range of flexibility which reduces breaks associated with earth movements such as settling or creep.

Materials used in any water-transmission system's construction, and its operation and maintenance afford ample sources of uncertainty with respect to potential system failures linked to biota transfers. For example, pipe materials may be more influenced by levels of organic matter in the system (see, e.g., Volk and LeChevallier 1999), since some materials provide better habitat for growth leading to observations of greater bacterial levels on iron pipes than on, e.g., PVC pipes (Norton and LeChevallier, 2000). Biofilms also develop more rapidly on iron pipes, even with corrosion control (Haas et al., 1983; Camper, 1996), and iron pipes support a more diverse microflora compared other materials (see, e.g., LeChevallier 1999a). Tuberculation of iron pipes also affects biofilm development, especially as systems relying on iron pipe age (Geldreich 1996). Materials that support microbial growth include polyethylene and bituminous coatings (Schoenen and Scholer, 1985; Frensch et al., 1987; Schoenen and Wehse, 1988), and lining materials (e.g., to control internal corrosion) may contain additives, solvents, or monomers capable of supporting microbial growth (Rigal and Danjou, 1999). Corrosion can occur internal or external to the pipe, and is variously affect by product-water chemistry, presence of iron and sulfur-oxidizing bacteria for internal corrosion, and the soil corrosivity, water table, and electrical grounding for external corrosion (see Section 3). As systems age, corrosion increasingly becomes a risk factor to address in operations and maintenance of the system, especially as corrosion contributes to or is directly linked to leaks in pipelines, valves, joints and seals. These individually or jointly may yield pipe breaks or bursts critical to enabling the biota transfer process.

Long-term operation of the water withdrawal, treatment, and transmission system is also a source of numerous uncertainties the preclude a definitive estimate of system failures adversely linked to biota transfer. Transmission system hydraulics is critical to operations yielding a system that meets performance criteria related to biota transfer. Hydraulic characteristics will influence system integrity, especially as that relates to, e.g., organic matter (such as DOC) that influences biological activity of biofilms developing within the system through time (see, e.g., Volk and LeChevallier 1999). For example, flow rates—system-wide or localized, e.g., system dead ends or near appurtenances—influence growth and survival of microbial communities characteristic of biofilms, so system attributes related to pipe configuration, material, condition and size, water demand, pump operation, and elevations must be viewed in the preliminary failure analysis as uncertainties that should be addressed in subsequent engineering investigations. Close interrelationships between system hydraulics and biota transfer may be highlighted by noting that water velocities through piping directly influence shearing of biofilms from pipe surfaces, with potential for dislodging and releasing microbes entrained in the biofilm. Such sharing events may be a mechanism that serves as an initiating event leading to biota transfer. Similarly, pressure transients may dislodge tubercles and shear biofilms that have accumulated in, e.g., low flow areas within the system (LeChevallier, 1990), resulting in release of elevated levels of the contaminants to the water column.

LeChevallier et al (2006, available at http://www.epa.gov/safewater/tcr/pdf/intrusion.pdf last accessed May 27, 2007) focused on risks linked to intrusion of contaminants into the distribution systems from pressure transients, which may identify similar risks in water transmission systems such as those outlined in DEIS (Reclamation 2007). While much of the current literature emphasizes the intrusion of chemical contaminants into water systems, the increasing awareness of risks associated with biological interlopers is characterized with uncertainty, especially as that reflects outcomes related to hydraulic behaviors of the system, e.g., pressure transients. Any change in fluid flow in a pipe (e.g., due to valve closure, pipe fracture, or pump stoppage) will result in an exchange of energy between flow and pressure, and the magnitude of the pressure change will be influenced by the materials of construction, pipe characteristics, and the water velocity. Hence, uncertainties associated with these system attributes must be considered in subsequent iterations of the design process. Operational characteristics can further affect the significance of pressure transients, including undulating topography, entrained air, valve characteristics, and frequent power failures of pumping stations (AWWSC 2002).

The significance of intrusion from a pressure transient—regardless of whether one's focus lies only in public health or in larger picture issues involving, e.g., fish and wildlife health—depends on the number and effective size of leaks, the type and amount of contaminant external to the distribution system, the frequency, duration, and magnitude of the pressure transient event, and the population exposed. Any contaminant exterior to the pipeline environment may enter the water transmission system, e.g., during a negative pressure event, with risk of intrusion increasing with system age. Biological contaminants are a concern because even with dilution, some microbes (e.g., viruses) could cause an infection with a single organism (see, e.g., Karim et al. 2001)

The frequency and magnitude of pressure transients reflect uncertainties that must be acknowledged in reiterative failure analyses companion to full engineering designs. Problems with low or negative pressure transients in water distribution networks have been reported in the literature (see, e.g., Walski and Lutes 1994, Qaqish et al. 1995), and could provide potential for entry of contaminants into water transmission and distribution pipelines. Surge control, particularly control of high-pressure events, has typically been considered for preventing pipe bursts and efforts have been directed at reducing the maximum pressures, yet negative pressure transients and their risk implications have only recently received attention. Mitigation or risk reduction measures potentially include, e.g., slow valve closure times, avoiding check valve slam, minimized resonance, air vessels, surge tanks, surge anticipation valves, air release valves, combination two-way air valves, vacuum break valves, check valves, surge suppressors, and by-pass lines with check valves (see, e.g., Cesario 1995, Skousen 2004). Efforts to reduce pipeline leakage are beneficial for water conservation, but also minimize risk potentials for microbial intrusion.

Uncertainties related to water transmission system aging. While this preliminary analysis simplified failures as being associated with water withdrawal, treatment, and transmission, a conceptual model of a process intended to address these and other infrastructural-related uncertainties is presented in Figure 33 and could be included in future investigations

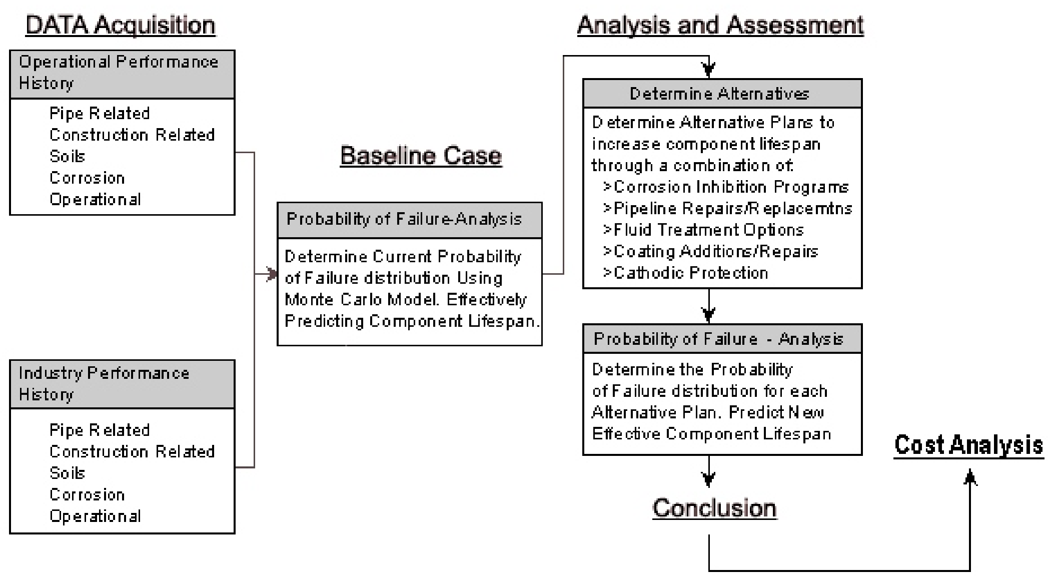

Figure 33. Process of life-cycle management for buried pipe (after EPRI 2001, modified after original figure posted at http://www.structint.com/ tekbrefs/datasheets/buriedpiping/).

focused on detailed engineering designs (see also USGS 2005b, 2006). As noted in Section 3 and in USGS (2005b, 2006), buried water transmission pipelines are subject to corrosion, soil movements, temperature fluctuations, rainfall, and system stresses in the continuous process of structural deterioration.

Various environmental mechanisms adversely affect long-term performance of buried pipelines, e.g., infrastructure degradation linked to various internal and external corrosion may be significant, leading to maintenance and repair issues as the transmission system ages. Depending on pipe specifications and materials and as piping ages, pipe and pipe coatings deteriorate (e.g., corrosion for iron pipe) which eventually leads to leaks or pipe breaks. Critical piping systems such as those proposed for addressing NAWS water needs rely on buried pipe whose failure can adversely impact transmission or (eventually) distribution lines. As noted in Section 3 and as standard practice suggests (see, e.g., Moser 2001 and references cited therein), in the northern Great Plains buried pipe will generally be placed no less than 7-7½ feet below ground surface (BGS) to prevent freezing. The effects of frost-heave will also be reduced, given burial follows guidance available for construction on various soil types , e.g., see http://www.soils.usda.gov/technical/handbook/ contents/part618p2.html#29, Andersland Ladanyi 2004, USDA–NRCS 2003), depending on required elevations for pipeline segments throughout the transmission system.

Pipe standards for materials and installation are specified by American Water Works Association (AWWA; see, e.g., http://www.awwa.org/bookstore/Category.cfm?cat=3), American Society for Testing and Materials (ASTM; see, e.g., http://www.astm.org/cgi-bin/ SoftCart.exe/COMMIT/COMMITTEE/C13.htm?L+mystore+jvks6413+1125547345, last accessed May 21, 2007), and American Society of Civil Engineers (ASCE; see, e.g., http://www.asce.org/ instfound/codesandstandards.cfm, last accessed May 21, 2007). For example, transmission and distribution lines constructed of DIP must withstand internal and external pressures, including pressure transients, and be resistant to corrosion (see AWWA standards and manuals, and guidance from National Association of Corrosion Engineers [see USGS 2006]; see also "Corrosion considerations for buried metallic water pipe" July, 2004, Bureau of Reclamation, Technical Memorandum No. 8140-CC-2004-1). As noted in Section 3, failure rates in DIP (as well as cast iron water pipes) are related to various soil properties, which may be mapped using geographical information systems (GIS) as illustrated in Figure 25 for soil properties linked to corrosivity, as estimated by soil electrical conductivity, potentially associated with soils in McLean and Ward Counties, North Dakota.

Cathodic protection has been incorporated into water transmission pipeline linking water withdrawn from Lake Sakakawea with Minot WTP. As such, cathodic protection offsets soil corrosivity. Stainless steel bolts have also been used as required in appurtenances to reduce the possibility of failure from corrosion. Cathodic protection has been a method of choice water transmission and distribution systems (see, e.g., Peabody 1970, Heidersbach 1998, Shipilova and LeMay 2005), and may effectively defer risks directly linked to system aging through the installation of sacrificial anodes made of magnesium or zinc (depending on soil characteristics) underground at pipe depth. The reader is referred to USGS (2006) for additional background on cathodic protection as a tool to offset corrosion-related uncertainties linked to the water transmission pipeline proposed for delivering water to Minot WTP.

Uncertainties associated with existing data on pipe and other system component failures. Encountered data incorporated into this preliminary failure analysis present attributes that unavoidably capture uncertainty reflected in the interpretation of risks. As noted in Section 2 and in USGS (2005a, 2006), encountered data are commonly collected in ecological and environmental studies, and are largely observational in character. In desktop analyses frequently completed in preliminary analyses, data are generally secondary (e.g., compiled by third parties such as government or industry sources) and are heterogeneous in nature. Yet, for preliminary desktop analysis, encountered data with their attendant uncertainties may better serve to identify project-critical data gaps, e.g., related to short-term and long-term system reliability.

For example, uncertainties in water transmission and distribution pipelines was considered by Boxall et al. (2004) in their efforts to forecast burst behavior of pipes. These workers observed a number of uncertainties potentially linked to interpretation of statistical results achieved in the analysis process, including those related to data quality and quantity, lack of association between individual events and pipes, and the statistical techniques applied in the investigations. Each of these uncertainties are also reflected in the preliminary failure analysis. Yet despite these uncertainties, the existing literature indicates strong associations between burst rate, diameter and length, and a complex association with age of pipe. Various sources suggest that factors influencing pipe failures reflect the wide range of physical, chemical and loading factors that exists in a water pipeline's operating environment. These factors interact, which also influences potentials for failure. Categorically, these factors linked to uncertainty are related to loading, pipe diameter and material, corrosion, age or time-in-service, pipeline length, and third party actions.

Loading requirements of a water transmission system vary, and serve as a design criteria for any system. Under operating conditions a pipe is provided with uniform support over its entire length, yet uncertainties in this preliminary failure analysis (or more comprehensive analysis completed in parallel to an extensive hydraulic evaluation) may be associated with, e.g., poor initial installation or disturbance over time related to ground movements. The ability of pipes to resist such forces is a function of the material strength and the second moment of the cross-section (closely captured by cross-sectional area as noted previously; see Figure 27), perhaps most easily conveyed by looking at pressure-handling requirements of pipe. Pipes are designed to resist internal pressures of water flowing through them, with pressure being an important factor controlling pipe leaks. Beyond routine operating pressures, pipes are also exposed to greater forces under transient conditions, induced by sudden changes in operational conditions, such as pump switching, power failure and valve movements. The ability of a pipe to resist the stresses induced by internal pressure is a function of the tensile strength of the material and wall thickness (see, e.g., Moser 2001). Clearly, pipe loadings reflect uncertainties related to pipe diameter and material among other factors. USGS (2006) should be reviewed for a detailed consideration of uncertainties linked to encountered data used in this analysis.

Global uncertainties reflected in preliminary failure analysis and system designs. Much of the preliminary analysis focused on NAWS alternatives hinged on existing failure data for pipe and components necessary to conceptual designs such as pumps, valves, and treatment processes. Given the relatively coarse-grain analysis supported by conceptual designs identified in the DEIS (Reclamation 2007), uncertainties directly related to the preliminary nature of the design are apparent. For example, given the list of factors briefly identified, composite failure rates were the only values supporting the analysis of risks associated with system failure. As noted in USGS (2006), composite values for failure rates for a variety of system components clearly underscore the analytical limitations of encountered data. Compilations of pipe break and burst data illustrate the uncertainties inherent to existing data, as those may reflect differences in derivation.

For example, across a variety of pipe materials, failures tend to increase exponentially as a function of time, e.g, in a study restricted to pipes greater than 8 inches (200mm) in diameter Andreou and Marks (1986) found that the time to next break decreased as each break occurred. Goulter and Kazemi (1988) found that failures were spatially-linked more often than not, e.g., failures tended to occur within a short distance of neighboring failures. Various explanations have been suggested to account for such occurrences, including soil movement caused by the changing moisture content from the leaking water or exposure of the soil to the extreme cold of the air and disturbance of the bedding during repair (see, e.g., Skipworth et al 2002). Regardless of the causal factors leading to such observations, these and other studies urge caution in the interpretation of any preliminary analysis. Mechanisms of pipe failure more often than not occur as combinations of loading and structural deterioration, and reflect a range of factors related to material, diameter, length and age.

Interpretation of risks characterized in this preliminary failure analysis focus on future iterations of the risk analysis-system design process. Design of a water withdrawal, treatment, and transmission system requires preliminary analyses in order to focus on questions that help identify levels of risk tolerance and the characterization of acceptable risks before moving the process beyond conceptual designs. Within the context of uncertainties constraining interpretation of this preliminary failure analysis, most of these uncertainities will be addressed in full engineering designs developed following revision of the DEIS (Reclamation 2007).

Overall, system integrity, particularly as those are captured by loss of pipeline reliability or failures in treatment processes, must be viewed within the context of uncertainty. For example, loss of containment commonly linked to leaks, breaks, and bursts have historically been associated with human factors (e.g., faults in construction and operation or other third-party actions), design flaws, materials failures, extreme conditions or environments, and most commonly and importantly, combinations of these factors. Recall that human factors related to third-party actions and breaches in system security were not considered in this preliminary failure analysis, yet these factors were identified in Table 8. Materials failures commonly linked to pipeline failures include mechanical damage (e.g., linked to installation), fatigue cracks and other material defects, weld cracks (as might be encountered in joint-welded pipes), and external or internal corrosion. Metal fatigue in pipelines and other mechanical components of the water withdrawal, treatment, and transmission system are commonly linked to repeated cycling of the system load and the progressive local damage linked to fluctuating stresses and strains on the material, e.g., metal fatigue cracks will be initiated and propagated in regions where the strain is most severe.

Understanding and communicating uncertainties and limitations associated with full engineering designs should be incorporated into risk management plans for any alternative. Developing these plans within the context of a system's life cycle directly addresses uncertainties reflected in the lifetime distribution of the system, which ultimately yields a more reliable system in its long-term operation and management. Life cycle analysis is a dynamic process that can help inform decision-makers, while reducing risks through design, construction, and operation of a system such as those envisioned to meet the water demands of the NAWS service area (see, e.g., http://www.epa.gov/ORD/NRMRL/lcaccess/lca101.htm last accessed May 14, 2007).

4.5 Uncertainties Associated with Competing Pathways as Confounding Risk Factors Linked to Interbasin Biota Transfers

Intensively controlled interbasin water transfer will likely not increase risk of species invasions and may reduce basinwide risks of species invasions, if control systems are incorporated into diversion system's design as indicated in Reclamation (2007) and offset risks linked to competing pathways in a basin-wide exposure scenarios. In contrast to project-specific pathways, pathways directly dependent on biological vectors may be highly diffuse and may become more prominent when human agents are integral to pathway (see Taylor and Irwin 2004 and Erickson 2005 for interactions between invasions and economic activities of human enterprise as those related to exotic plants and aquatic nuisance species, respectively). For example, non-food animal pathways are currently recognized as critical components in the invasion process, e.g., aquaculture from supplier to buyer (e.g., spanning distance from facilities where organisms are raised, transporting organisms from facilities to wholesale distributors, and to retail outlets). NISC also considered nested, subordinate pathways as lower-level components in the invasion process (and referred to as "subpathways"), e.g., intentionally released (authorized or unauthorized) or escaped biota derived from aquaculture trade, hitchhikers that occurred on or in cultured organism (e.g., parasites and pathogens), and biota that occurred in water, food, growing medium, nesting or bedding. From a systems analysis perspective, the invasion process linked to the bait industry (recreational or commercial) would be similar to that for the aquaculture industry in both food and nonfood modes. Here, releases would involve in-trade bait organisms either intentionally (authorized or unauthorized) or unintentionally released (e.g., escaped or accidental), and hitchhikers associated with bait organisms (e.g., parasites and pathogens) or in water, food, growing medium, nesting or bedding, or organisms subject to transport.

Other human-agent dependent-pathways also contribute to misinterpretation of causal linkages between sources and the appearance of invasive species (e.g., observation of founder population). NISC recognized the role that interconnected waterways, including interbasin water transfers, potentially play in linking disjunct biota by creating pathways that promote species invasions. For example, historic examples of species invasions reinforce the importance that preventing or controlling species invasions have as resource management issues, e.g., interconnected waterways (e.g., Chicago Ship and Sanitary Canal and links between Upper Mississippi and Great Lakes basins) and interbasin transfers (e.g., California Aqueduct and All American Canal in the southwestern US; see NRC 1992). These interconnected waterways may be considered derivatives of a larger set of ecosystem disturbances that reflect "short-term disturbances" such as habitat creation, restoration, enhancement and forestry that facilitate introduction. Similarly, “long-term disturbances” such as rights-of-way for utilities and transportation corridors (pipelines, power lines, rail lines, and roads), land development including agriculture and logging practices, surface water management including dam construction and stream channelization may also facilitate introduction.

From a technical perspective, it remains difficult to distinguish between dispersal directly or indirectly linked to “human agency” and dispersal that occurs by a “natural process.” While many dispersal events and the subsequent establishment of invasive species populations are strongly linked to human activities (e.g., Ruiz and Carlton 2003), distinguishing between these processes and the dispersal, establishment of sustainable populations, and continued spread of invasive species as a process not reliant on human intervention may present intractable or costly questions. These costs may be even greater, if technical analysis of shifts in metapopulations is necessary for implementation of a water resource management plan. Examples of dispersal and species invasion occurring independently of human agency are numerous, including migratory events, movements of propagules and spread of previously established populations via water and wind currents (including movements of particulate materials such as dusts), unusual weather events (e.g., hurricanes), and spread as hitchhikers on migratory mammals and birds. Dispersal without the intervention of human agency has a long history (see MacDonald 2003; Bullock et al. 2002; Colbert et al. 2001). Such natural processes occur in the absence of human agency, and prior to human occurrence, were the drivers behind dispersal, establishment, and expansion of any species distributions before invasive species acquired their current sociopolitical and socioeconomic status.

Pathways and life history attributes characteristic of invasive species are highly linked, and as such, life history attributes may guide pathways analysis to prevent, or at least minimize, dispersal of any species into areas previously outside their current distribution. As evidenced by biological invasions that have occurred in the past, Scientific Committee on Problems of the Environment (SCOPE; see http://www.icsu-scope.org/ last accessed July 10, 2007, see also http://www.icsu-scope.org/projects/complete/gisp.htm) noted invasions tended to be initiated by stochastic events, which made the initiation of any particular invasion poorly predicted. Accordingly, SCOPE launched an approach wherein the study of invasions became statistical, characterizing the probability of outcomes for classes of invasions. While the current investigation found data sufficient to categorize each of the biota of concern with respect to their overall risk of invasion directly associated with interbasin water transfers, we were unable to quantitatively compare competing risk scenarios related to transfers via alternative pathways. The inability to complete a strictly quantitative comparison between “project risks” and “not-project risks” (e.g., statistical comparison between alternatives) stemmed from two interrelated primary factors.

One, quantitative empirical data were insufficient (e.g., small sample size) to adequately characterize frequencies associated with nodes within a given non-project scenario’s flow-of-events. Insufficient data generally result in an inability to use observed frequencies to characterize probabilities associated with transfers between steps in the invasion process regardless of efforts to collapse multiple-step processes into simpler two-step systems (i.e., reduce granularity of risk scenarios). Two, developing a general process scenario based on risk associated with project activities was comparatively simple relative to alternative pathways (human agency or not), and empirical data supporting this general scenario, although sparse, were available for an interpretation of risks associated with "project" activities such as failures (e.g., breaks in distribution pipeline and limits of filtration technologies proposed as alternatives in control systems designed to implement water diversions). While simulation data served the purpose for these comparisons of relative risk, quantitative data from the existing literature and public-domain sources were insufficient to warrant statistical comparisons.

4.6 Potential Failures and Their Associated Risks and Uncertainties

Differing perceptions of risk will affect acceptance of alternative of choice, yet if water needs and demands motivate greater specification in engineering design and cost analysis following revision of the DEIS, the preliminary failure analysis considered in this investigation may help identify which engineering tools—be those related to source water withdrawal, biota treatment, or water transmission functions of the system—may contribute to risk minimization criteria that might capture stakeholder support. The current investigation must not be considered an engineering evaluation beyond the technical observations that have considered failure of systems or system components as factors potentially contributing to biota transfers. Engineering costs have not been considered in this study.

Provided the background in USGS (2005a,b, 2006), the preliminary failure analysis provides a technical perspective to help focus detailed engineering designs intended to minimize biota transfer risks. While biota transfer issues are not primarily driven by public health concerns, the technical specifications of LT2ESWTR may provide tools capable of addressing small-bodied propagules such as disinfection-resistant life stages of fish diseases (such as *M. cerebralis*) and agents of infectious diseases of wildlife that are zoonotic in character (see USGS 2005a). DAF, membrane technologies or media-based filtration options (e.g., sand filtration) might serve risk management needs of NAWS focused controlling passage of infectious agents in source waters, depending on the risk tolerance of Reclamation and stakeholders.

Consistent with guiding principles considered in USGS (2005b, 2006), two general attributes of a risk—the spatial attribute, or "where source water will be withdrawn" and the implementation attribute, or "how the water will be delivered" to the Souris River basin—have guided this analysis and should continue to influence specifications of engineering designs developed consequent to outcomes of the DEIS. Each alternative is equally responsive to this aspect of the spatial attribute, since locations for withdrawal and biota treatment rely on controls systems near Lake Sakakawea in the Missouri River basin where a treatment facility to be specified should ensure waters destined for transfer have passed through biota transfer countermeasures intended to reduce risks.

If each of the four alternatives identified in Reclamation (2007) were moved forward to detailed engineering design, biota transfer risks would be reduced, but might not be minimized and would likely not be optimized. In part this stems from the absence of regulatory benchmarks specific to biota transfers and no promulgated standards specifying acceptable risks related to species invasions (USGS 2005a,b, 2006). Implementing interbasin water transfers with controls systems proposed in the DEIS would encourage resource management discussions focused on system of control technologies that could optimize designs that must be responsive to competing risks that include those related to biota transfers. As noted in USGS (2005a), the spectrum of organisms identified as biota of concern display a wide range of life history attributes that may influence choices for risk-reduction tools considered in engineering final design. Given concerns regarding biota transfers throughout the lifetime of any system delivering water to the Souris River basin, system upgrades should be anticipated, especially as water treatment technologies mature. As such, biota transfer countermeasures might be maximized by using integrated water treatment technologies currently included in conceptual designs. Costs related to mounting multiple countermeasures would require engineering scrutiny, yet a mix of available technology would yield a control system sufficient to offset biota transfer risks commensurate with Reclamation and stakeholder risk tolerance.

5.0 Summary: Managing Water Resources and Risks Associated with Potential Biota Transfers

Each proposed biota-water treatment alternative posited by Reclamation (2007) is predicated on disinfection of source waters to reduce risks associated with unintended biota transfers potentially realized as events collateral to an interbasin water diversion. Within this context, Reclamation has considered a range of biota-water treatment options that involve a variety of technologies to reduce biota transfer risk while meeting the water needs of a wide range of users, including drinking water, municipal, and industrial applications. This section opens with an introduction of life-cycle assessment as a tool potentially applicable to developing adaptive management plans responsive in part to risks that will continually challenge the infrastructure and operation of water projects targeted on the NAWS service area, then closes with a brief summary of technical findings for this risk analysis and characterization study.

5.1 Life-Cycle Assessment

The current analysis captures a snap shot of a conceptual system's lifetime that may well change before a final selection of alternative of choice, e.g., engineering designs will be develop, and eventually become final, wherein greater specification in design elements would support a more fully implemented engineering reliability analyses of the control system and its components. Given the early design attributes of the alternatives considered in the DEIS (Reclamation 2007), risk management plans warrant a "life-cycle assessment" framework for future analysis.

5.1.1 Life-Cycle Assessment (LCA). Because of legislative and regulatory mandates such as National Environmental Policy Act (NEPA) of 1969 as amended ([Pub. L. 91-190, 42 U.S.C. 4321-4347, January 1, 1970, as amended by Pub. L. 94-52, July 3, 1975, Pub. L. 94-83, August 9, 1975, and Pub. L. 97-258, §4(b), Sept. 13, 1982)] 40 CFR Section 1502.14(d)), business, industry, government agencies, and stakeholder groups have undertaken a range of activities in response to historic observations focused on land-use and water-use practices that potentially affect the environment. While broadly applied across a range of environmental practices, many organizations explore ways to improve environmental performance. Consequently, life cycle assessment (LCA) has developed as a practice that considers the entire life cycle of a process or product.

For most systems, LCA is a "cradle-to-grave" approach to environmental analysis that addresses, e.g., a manufacturing or construction process, beginning from gathering of raw materials or initiating a construction activity, then moving forward to manufacturing products or developing maintenance and operations for a completed project, and ending with plans for end-of-life management or decommissioning. Each of these aspects of LCA may be assigned to lifetime plots typically captured in the bath-tub curve, with LCA potentially serving as a parallel evaluation of all stages of a product's or process's life, particularly their interdependencies given operations are commonly interdependent. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in an activity's or product's "life history." Such an analysis of life history means LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of environmental trade-offs in product selection (see, e.g., ISO 1998a,b, ISO 1997).

LCA is an analytical method that assesses environmental aspects and potential impacts associated with a product, process, or service, by:

- compiling an inventory of relevant energy and material inputs and environmental responses,
- evaluating the potential environmental impacts associated with identified inputs and responses, and
- interpreting the results to help risk managers make more informed decisions.

As with HACCP, the LCA process is a systematic and phased analytical approach applicable to risk management. LCA may also contribute to a decision-making process, e.g., selecting between two alternatives through comparisons of lifetime costs (monetary and non-monetary) captured by the process under consideration. LCA may help decision-makers select the products (e.g., pumps and valves) or processes that result in the least impact to the environment (e.g., selection of pipeline route for NAWS water distribution network), which may link to other factors such as cost and performance data that relates to making a decision. Through LCA, tracking environmental impacts associated with alternative actions can help decision makers and managers fully characterize environmental trade-offs associated with prospective changes to land-use and water-use. For example, once engineering designs for an alternative of choice have been identified for serving the water demands of populations of the Northwest Area, incorporating LCA into future evaluations could extend this preliminary failure and consequence analysis within the context of adaptive management. Although this preliminary failure analysis does not implement an LCA, the framework supporting that analysis could rely on existing guidance (see, e.g., ASTM 2006d, FAO/WHO 1998, WHO 1997), which may serve subsequent engineering design and cost analysis once alternatives of choice are identified.

5.2 Summary Findings for the Analysis of Risks Associated with Interbasin Biota Transfer Potentially Linked to NAWS

Regardless of technology of choice, no control system will be "risk free." Each of the water treatment technologies posited by Reclamation (2007) presents risks associated with their use as part of a control system; those risks cannot be avoided but can be minimized. Given the competing risks characteristic of resource management activities, risk optimization should also be considered, since minimizing one set of risks, e.g., related to biota transfer may unintentionally elevate other risks within a multiple stressor exposure system. Risks associated with single-stage control systems such as those captured in Alternative A may be unacceptable for water resource managers, especially given the wide range in risk tolerance characteristic of risk managers guiding project development. While multiple-stage control systems are generally associated with less risk than those associated with a single-stage control systems, the concept of "zero risk" remains unattained even with the level of design captured in Alternatives B, C, and D (see, e.g., Schippers et al. 2004). Moreover, multiple-stage control systems will never be characterized by zero risk given the inevitable changes in a system's reliability through time. Potential system failures contribute to our inability to attain a "perfect system" having zero risks. Technical findings summarized in this report do not recommend one control system over another with respect to specification or configuration, nor do these findings specify whether risks are acceptable and not acceptable. This initial iteration in the analysis of risks, however, suggests that risk associated with biota transfers could be reduced through implementation of water diversion via a multiple-stage control system that incorporates pre-treatment followed by disinfection using a chemical (e.g., chlorination-chloramination) or a physical process (e.g., DAF, membrane filtration).

Risk management: The role of monitoring and mitigation plans as part of implementation. The brief consideration of the environmental setting for evaluating habitats at-risk illustrates the significant role that monitoring and mitigation planning plays in adaptive resource management, particularly within the context of managing risks related to biota transfers. Folding the ideas of integrated and cumulative effects into a framework of competing risks is operationally simple, since it merely extends the existing framework available for evaluating risks associated with multiple stressors (see, e.g., Foran and Ferenc 1999, Ferenc and Foran 2000). Developing monitoring and mitigation plans for managing risks associated with biota transfers or with species invasions as components of integrated and cumulative effects might offset uncertainties linked to system performance through time. Regardless of decisions related to interbasin water diversions and the control system developed to offset attendant risks, adaptive resource management plans should be developed, including monitoring and mitigation activities designed with a particular emphasis on their roles in ministering to uncertainty (see, e.g., Walters 1986, Wittenburg and Cock 2001).

A solitary focus on interbasin biota transfers uniquely linked to water diversions from the Missouri River technically oversimplifies the species invasion process, and reflects political and socioeconomic drivers that influence the risk assessment process. Risks exists in a changing landscape of time and space, and the risks associated with interbasin biota transfers illustrate such an observation. International Joint Commission's findings of unacceptable risks associated with biota transfers consequent to water diversions envisioned in the mid-1970s and early 1980's (IJC 1977) were amply justified given the "best management practices" available at that time, yet given the control technologies developed in the intervening 30 years, revisiting those findings may be warranted. Depending on the definition of acceptable risk, the current investigation characterizes risks for interbasin biota transfer linked to NAWS activities as low to very low for those biota of concern identified as long as control systems are sufficient to the task of risk reduction (e.g., multiple-step control systems involving pre-treatment, chemical and physical treatments, and filtration). Even then, however, risks of biota transfer will never be zero. Competing pathways will likely lead to interbasin biota transfers and subsequent species invasions in the near future, following the trend that has lead to species invasions of both Souris Rive and Red River basin in the past. In the absence of waters from the Missouri River basin entering the greater Hudson Bay watershed, species invasions have occurred, oftentimes mediated through human agency. In part, any control system's long-term performance is critical to offsetting these biota transfer risks; hence, life cycle assessment may be incorporated into adaptive management plans developed to support future implementation of the selected NAWS alternative.

Not surprisingly, our technical findings indicate risks of biota transfers will vary as a function of control system and time, particularly given the long-term water needs and demands of the Northwest Area. Although biota transfers and species invasions are subject to inevitable stochastic events, risks of biota transfers associated with interbasin water diversion implemented with multiple-staged control systems in place present low to very low risks and do not appear as significant as those biota transfer risks forecasted nearly 30 years ago when control options considered by IJC (1977) were relatively limited. To a large extent, the observed "risk reduction" apparent between 1977 and 2007 stems from advances in water treatment control technologies, which enable a project's final design be based on performance criteria developed within the context of acceptable risk.

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